Electron Beam Pumped Krypton-Fluoride (KrF) Lasers for Fusion Energy

A Tutorial
by
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Work proudly sponsored by DOE/NNSA/DP

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Main points of the talk

What is a KrF Laser?

Electron beam pumped gas laser

KrF Lasers for Inertial Fusion Energy

Strengths: Beam uniformity, zooming, cost, scale to large systems

R&D required: efficiency and durability

The Physics and Technologies of KrF Lasers

Electron beam propagation, transport, and deposition

KrF Kinetics

Pulsed Power

Phased program to develop a KrF Fusion Driver

Part of an integrated program to develop laser fusion energy

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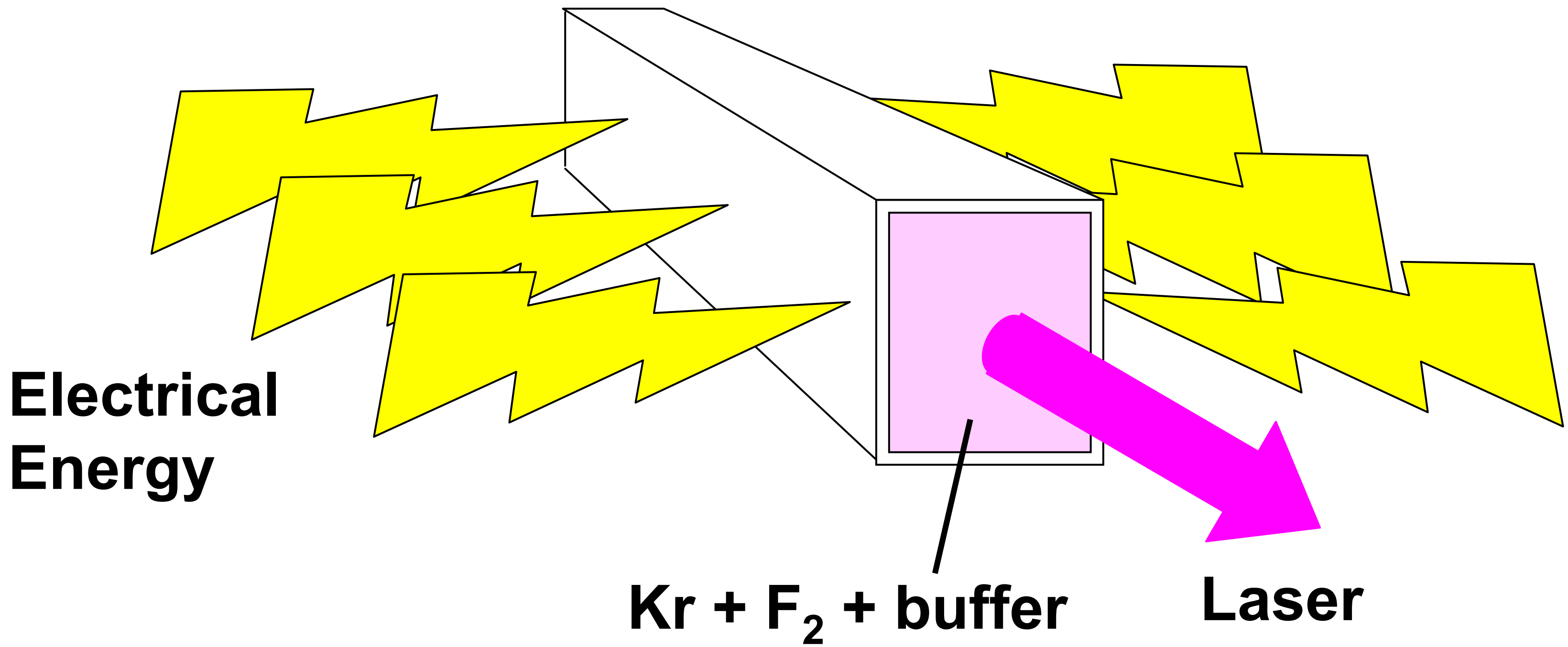
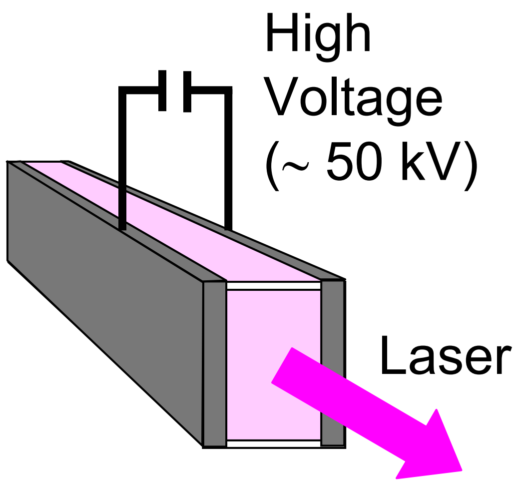
A Krypton Fluoride (KrF) Laser--- Gas Medium, Electrically Pumped

Energy + (Kr+ F_2) $\Rightarrow$ (KrF)* + F $\Rightarrow$ Kr + F_2 + hν (λ = 248 nm)



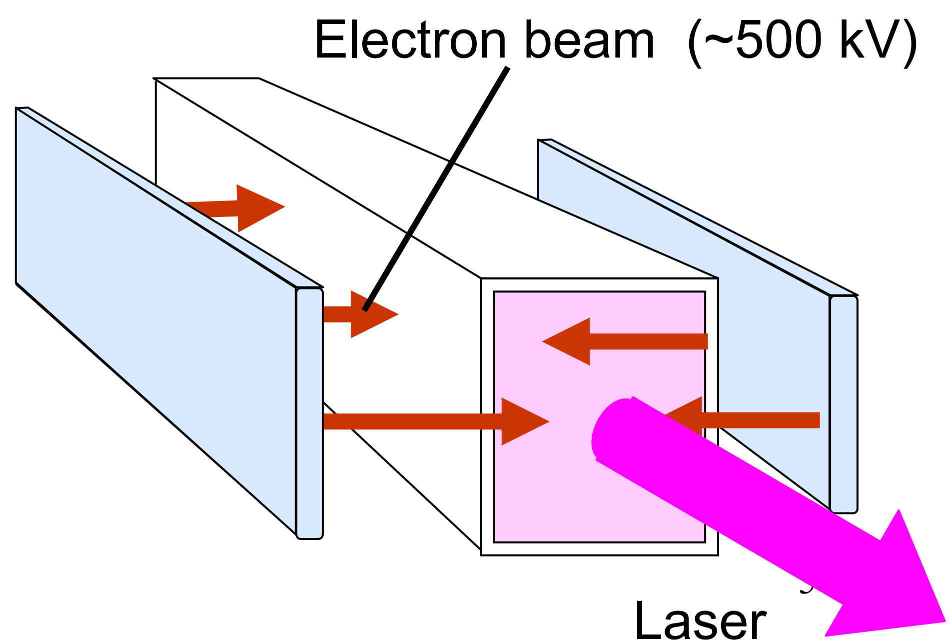
Large KrF Lasers are pumped with electron beams

Small Systems (< 1 J, < 10 ns)
(Semiconductor manufacturing)
>> *DISCHARGE PUMPED*



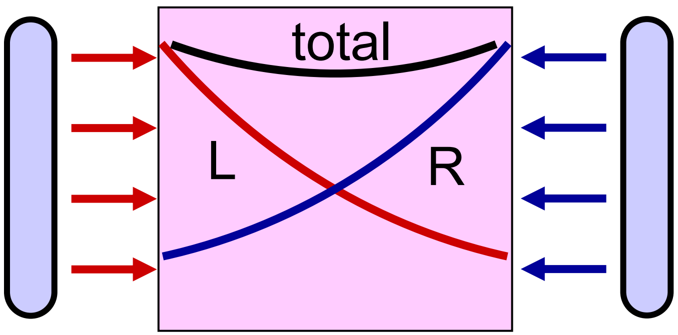
Cymer
NanoLith™ 7000

Large Systems (10's kJ, 100' ns)
(Fusion Driver)
>> *ELECTRON BEAM PUMPED*



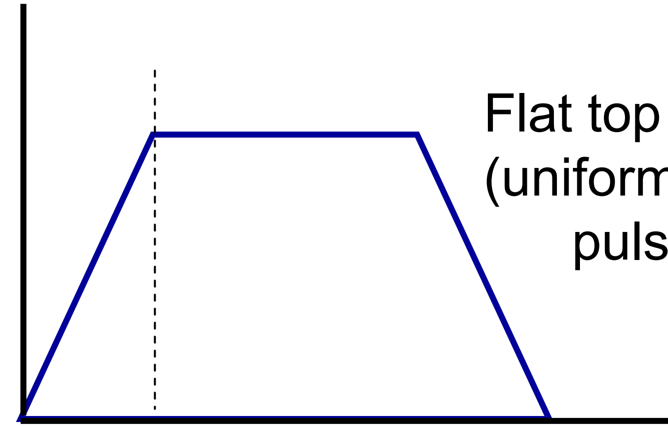
E-beam considerations

Beam Voltage



- Cell length: window size
- Gas pressure: physics + mechanical constraints
- Adjust voltage for uniform energy deposition

Power Waveform



Flat top (uniform laser pulse)

Fast Rise (efficiency, ASE)

High *__Laser Energy__* requires high *__E-Beam Energy__* $= \int_0^{\tau} IVdt$

V $\Rightarrow$ fixed by gas deposition requirements 300-800 kV
I $\Rightarrow$ limited by diode physics (impedance) to > 0.5 to 1.0 V
$\tau \Rightarrow$ limited by diode physics (impedance collapse) to < 1000 nsec

The key issues for KrF are being addressed with the Electra and Nike Lasers at NRL

<u>Electra:</u>
> 400 J laser light
500 keV/100 kA/100 nsec
5 Hz; 100,000 shots (5 Hrs)

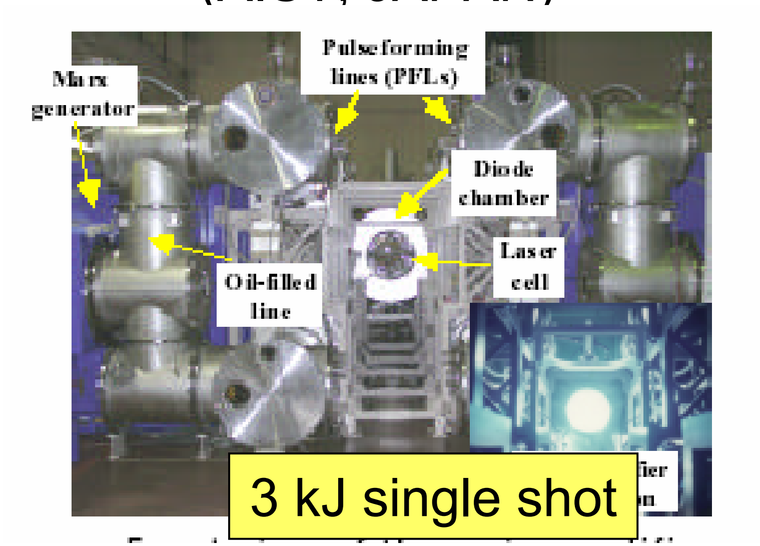
Develop technologies for:
- *Rep-Rate,*
- *Durability,*
- *Efficiency,*
- *Cost*

<u>Nike:</u>
3-5 kJ laser light
750 keV, 500 kA, 240 nsec
single shot

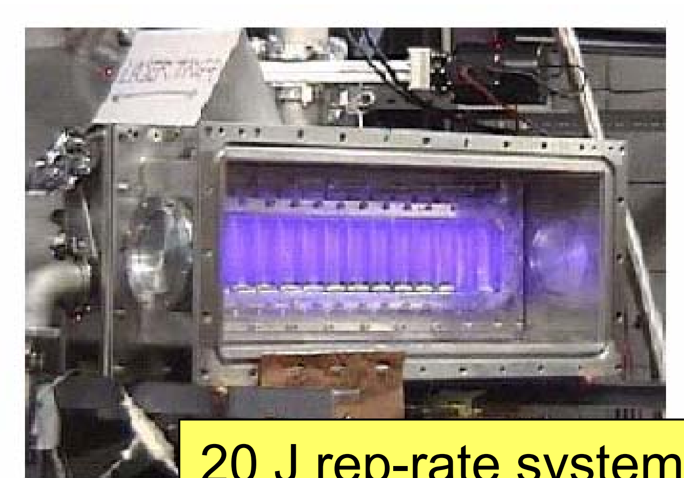
E-beam physics on full scale diode
Laser-target physics

Other KrF laser facilities

ASHURA
(AIST, JAPAN)

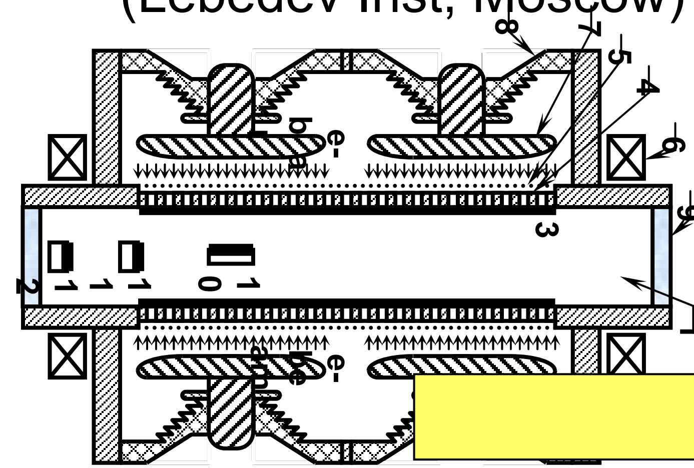


3 kJ single shot

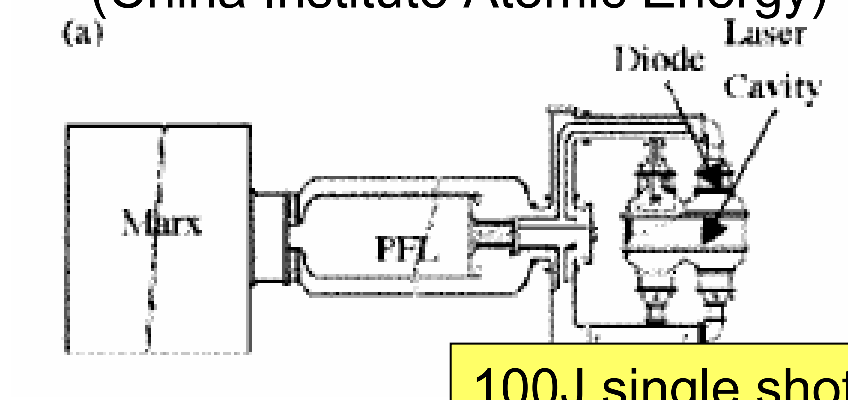


20 J rep-rate system

GARPUN
(Lebedev Inst, Moscow)

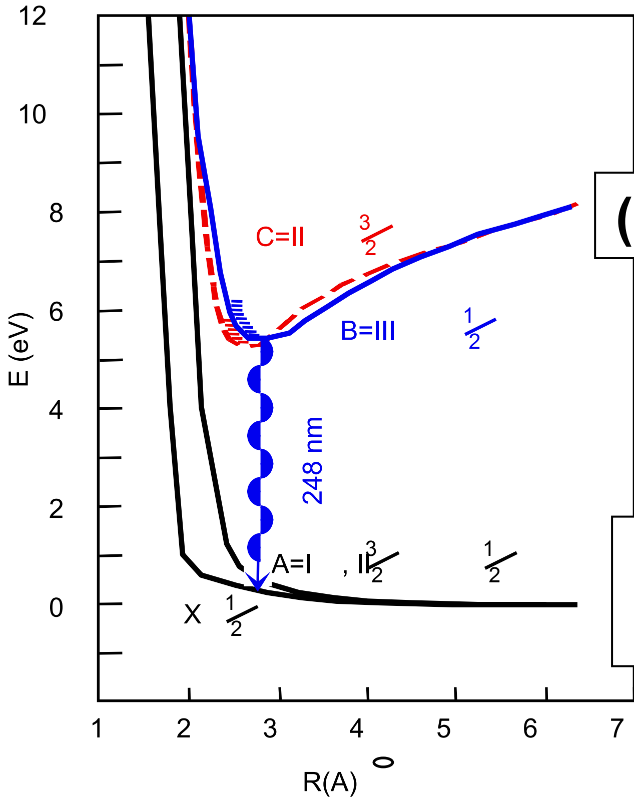


Heaven-I
(China Institute Atomic Energy)



100J single shot

KrF is an Excimer (Excited Dimer) laser.
1. Molecular electronic transition
2. Ground state immediately dissociates



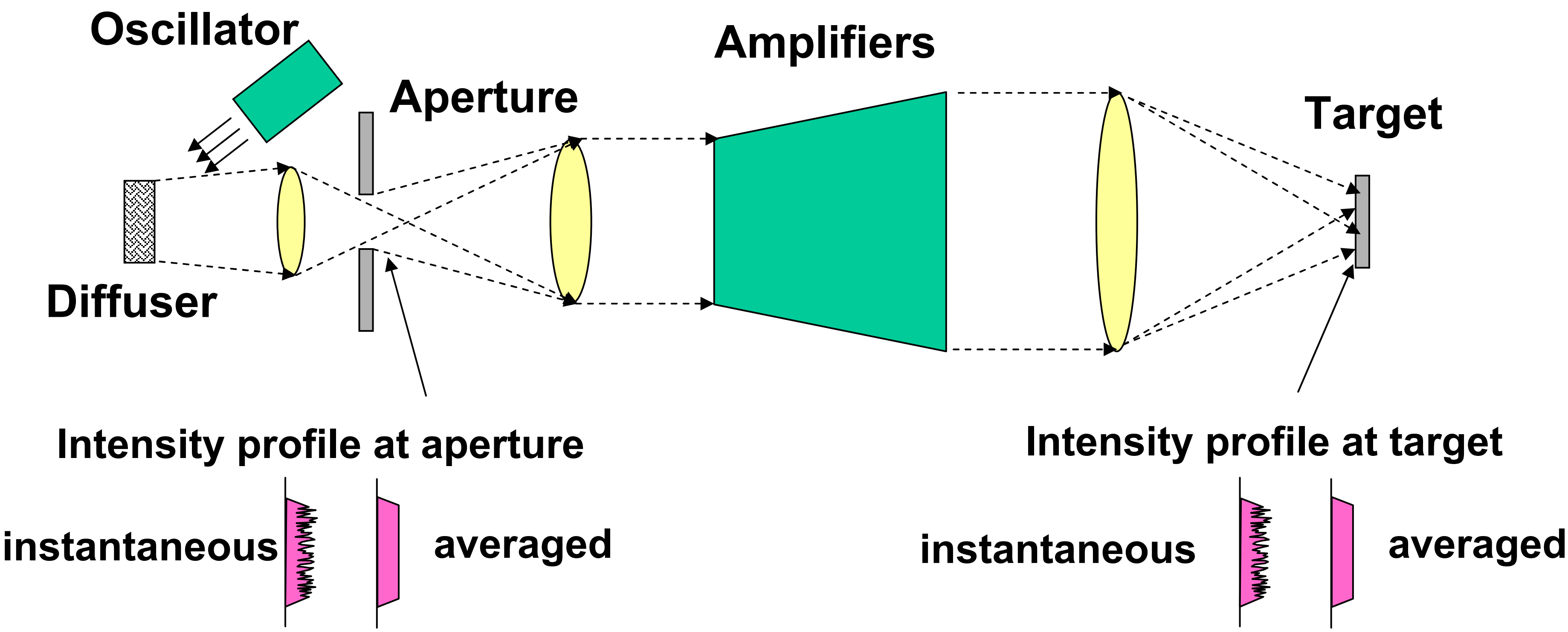
(KrF)* -- *excited state*

KrF-- ground state--
(dissociates as potential is repulsive)

Two key features of KrF:

1. Large Bandwidth: 1-3 THz
   no well-defined rotational/vibrational transition
2. Fast relaxation times: ~ 6 nsec

Large bandwidth of KrF means short averaging times. Hence rapid smoothing of the beam spatial profile. Result: Very uniform illumination of target

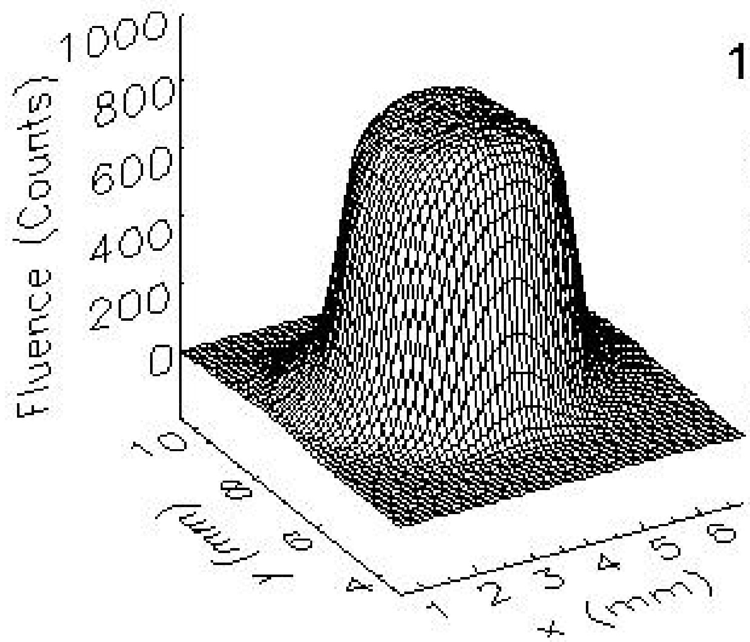


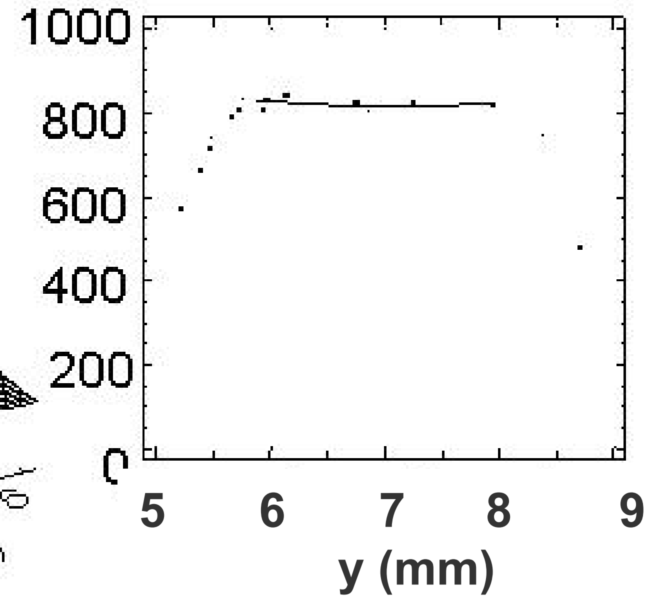
The laser profile at the aperture is imaged through the amplifiers onto the target

If the optical distortion is small, then the image duplicates the aperture

Concept of *Induced Spatial Incoherence* (ISI)

The NRL Nike KrF Laser (3-5 kJ) produces very uniform focal profiles





For 50% of the FWHM diameter:

Power tilts < 2%

Quadratic curvature: < 3%

RMS speckle non- uniformity: 0.3 - 1.3% (*all modes*)

Time scale miss-match #1:

6 nsec: Relaxation time of (KrF)*

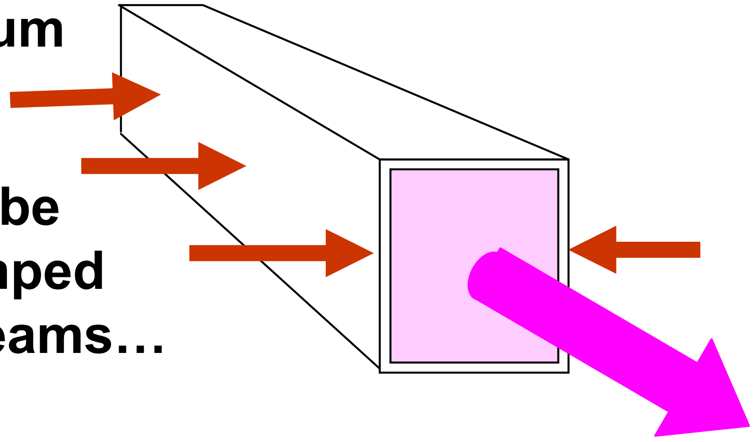
vs

100's nsec: E-beam (pulsed power)

Solved by continual pumping and extraction

KrF is not a storage medium

So Kr +F_2 must be continually pumped with electron beams…



….while laser energy is continually extracted

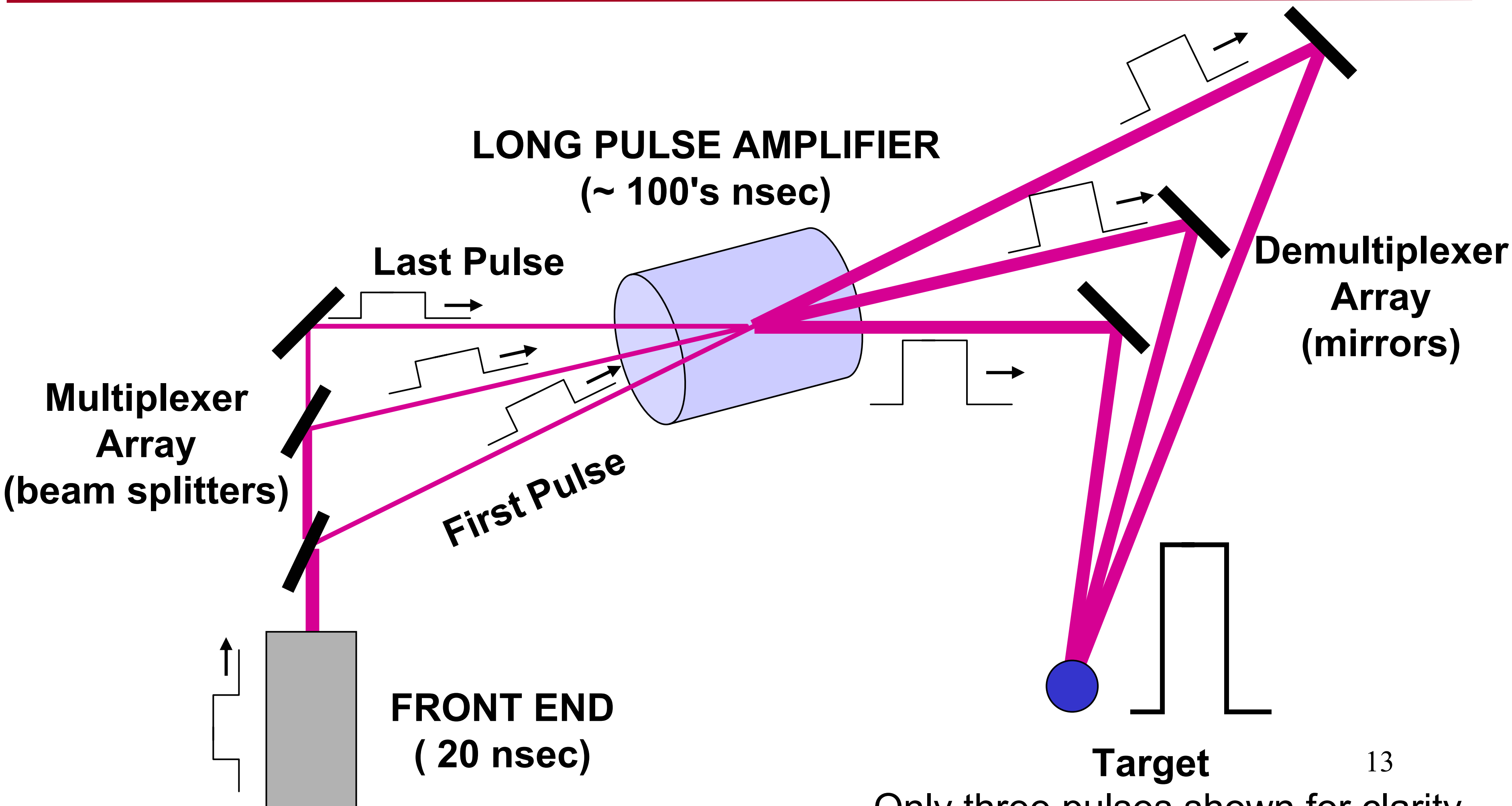
Timescale miss-match #2:

~ 8-16 nsec: Target Physics time scale

vs

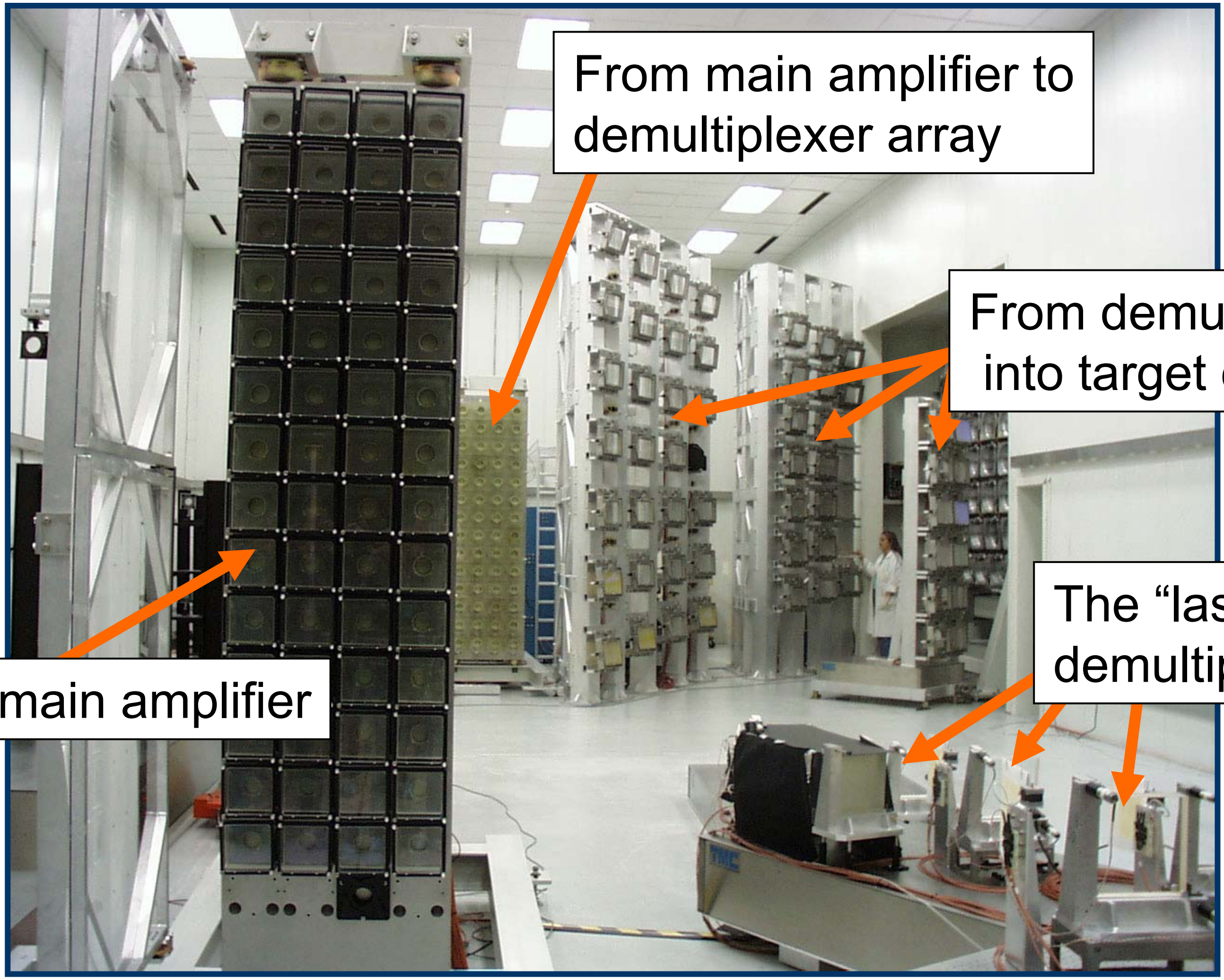
100's nsec: E-beam (pulsed power)

Solved by angular multiplexing



Only three pulses shown for clarity

The Nike Laser demonstrates routine use of angular multiplexing



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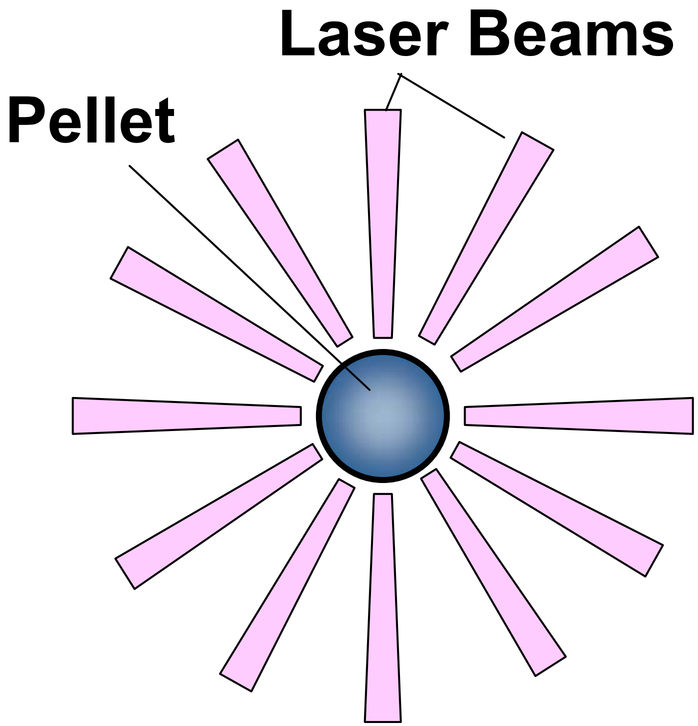
Direct drive approach to fusion energy



Just might work!

-- 1-D gains > 100,   2-D being calculated

Higher efficiency

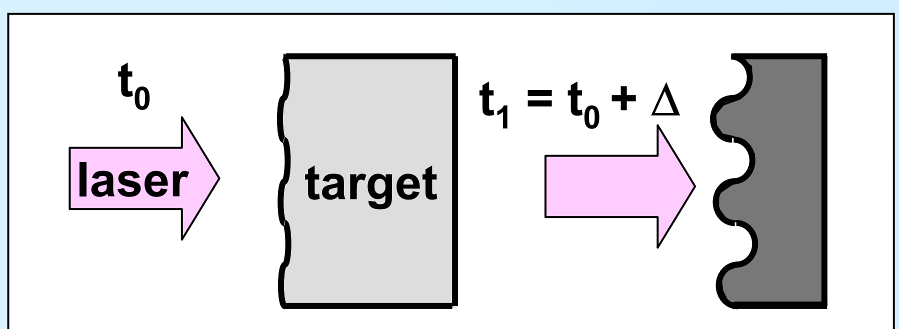
--better coupling of laser to fuel

Targets relatively simple (cheap) to fabricate--

--key issue is injection

Physics is simpler

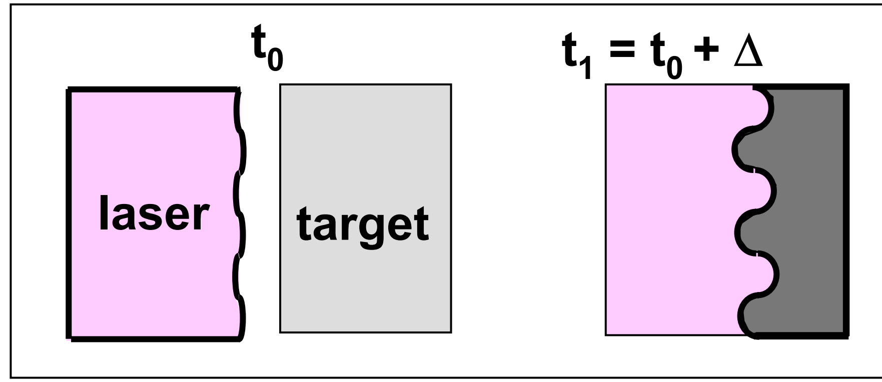
--key issue is hydrodynamic stability

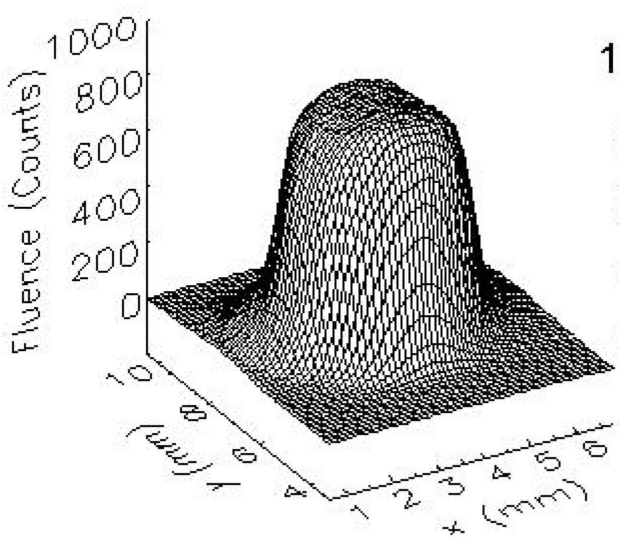


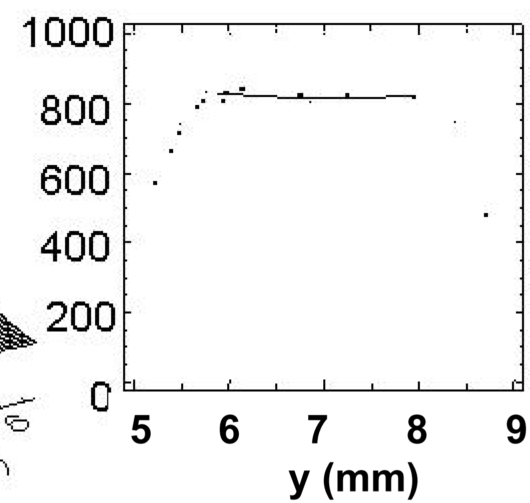
KrF lasers produce very uniform laser beams
Reduces "Imprinting" by laser

"Imprinting"--
Modulations imposed on target
due to non-uniformities in laser..

"Seed" for Rayleigh Taylor Instability

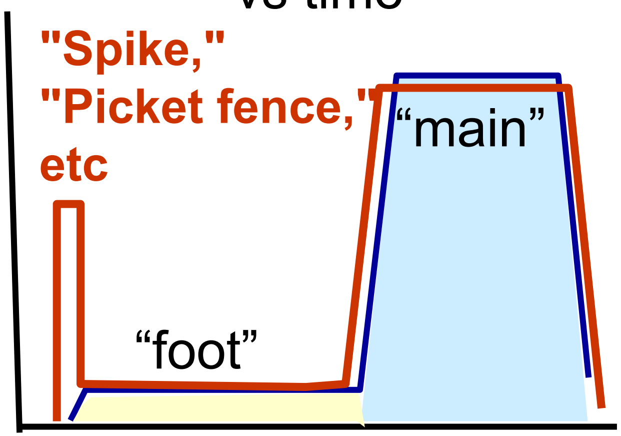






Shape laser pulse to help raise ablator isentrope:

Laser Intensity
vs time

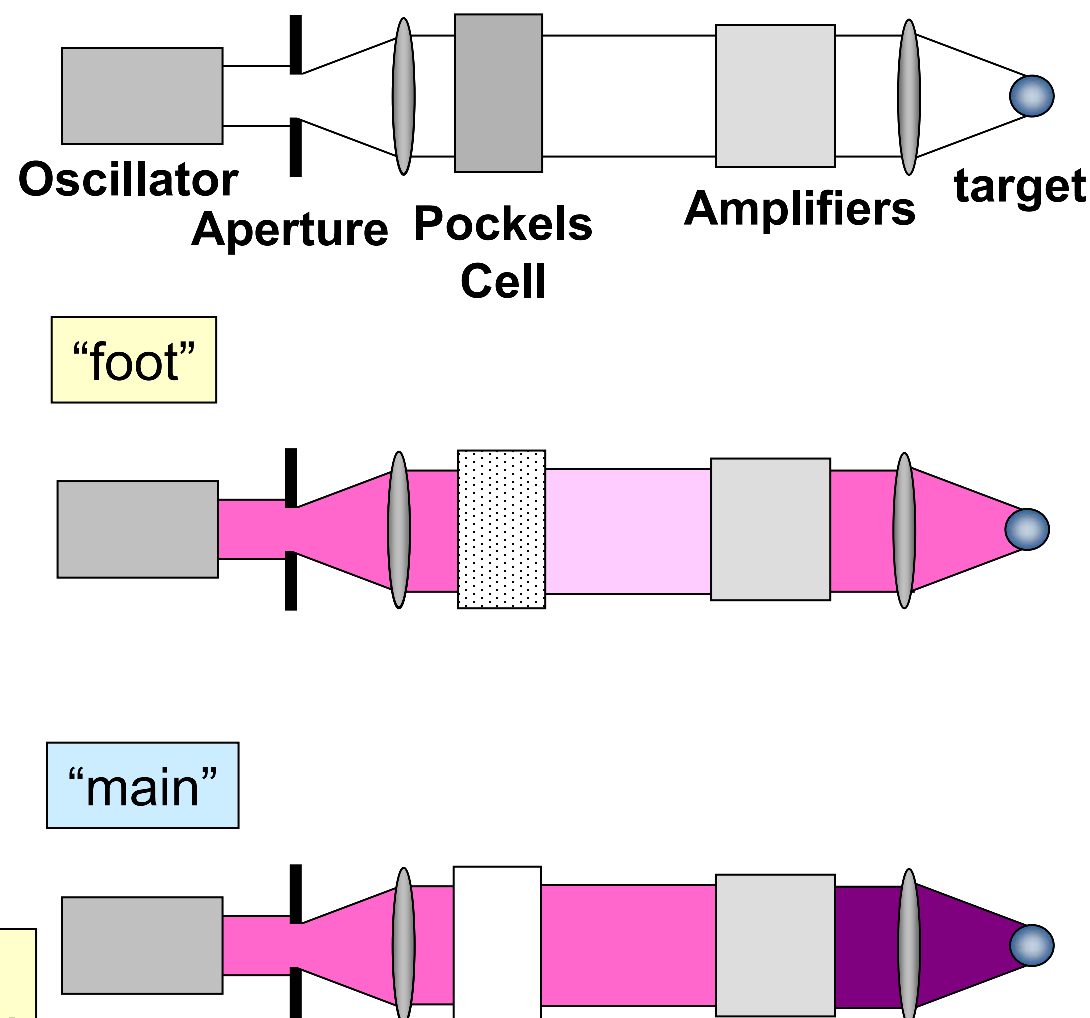


Low intensity foot launches mild shock through ablator, preheats it to raise isentrope

Can accommodate odder pulse shapes

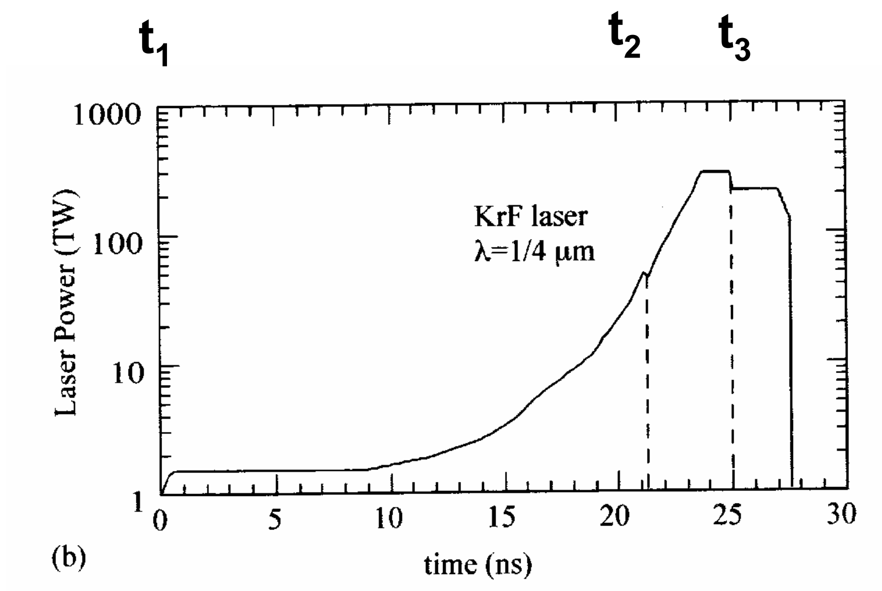
ALL ICF LASERS HAVE
PULSE SHAPING CAPABILITY

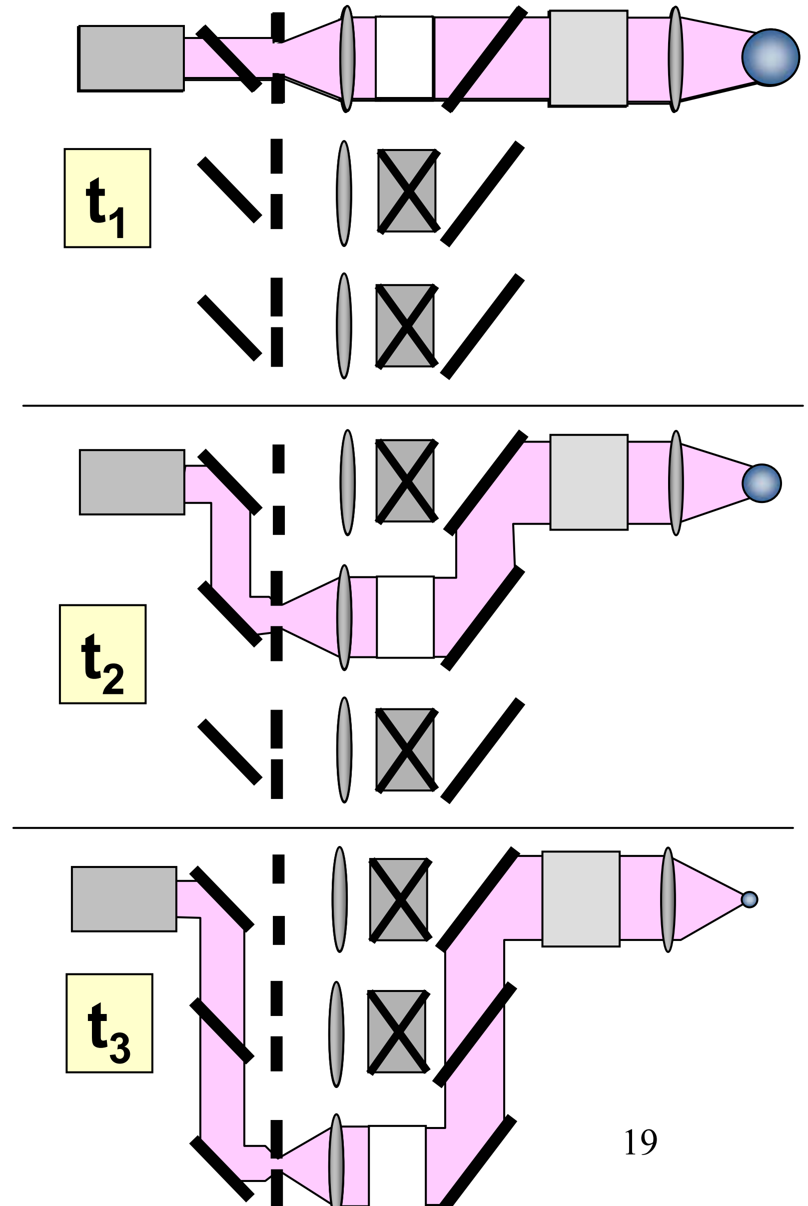
OPTICAL TRAIN OF KrF LASER



Straightforward with KrF to "Zoom" laser beams. This can boost laser absorption substantially (30%)

Decrease the laser focal spot
to follow the compressing target

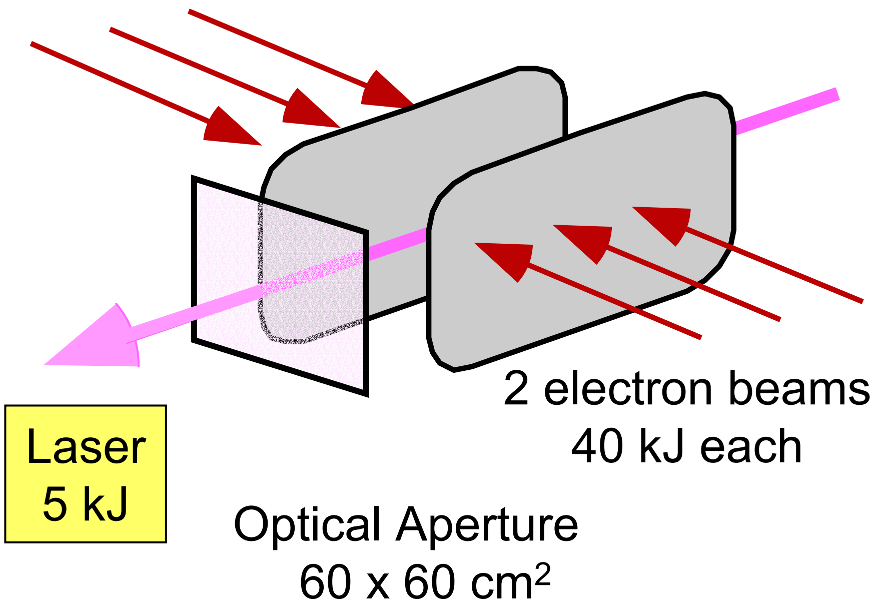




KrF driver would be modular: 30-40 identical amplifiers
The amplifiers would be made of modular components

WHERE WE ARE NOW…..

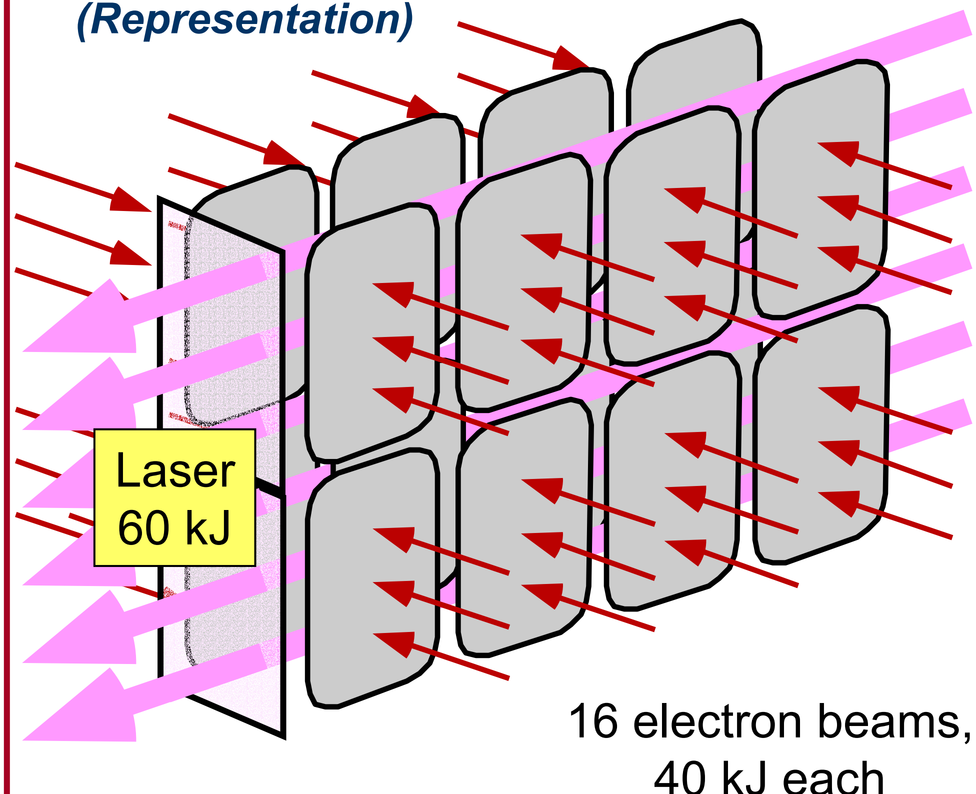
Nike 60cm Amplifier - 5 kJ output



WHERE WE WANT TO BE….

IFE-sized Amplifier- 60 kJ output

(Representation)



Optical Aperture
~80 x 160 cm^2

Assessment of KrF lasers for a fusion driver

Advantages

Beam uniformity

Simple zoom, pulse shape

Modular and scalable;

Lowers develop costs

Pulsed power based

Low cost, industrial technology

R & D Challenges

Efficiency:

12 % Intrinsic KrF
80% Pulsed Power
80% Hibachi
90% Auxiliary
= 7 % total
(OK for target gain > 100)

Durability:

3×10^8 shots (5 Hz @ 2 years)

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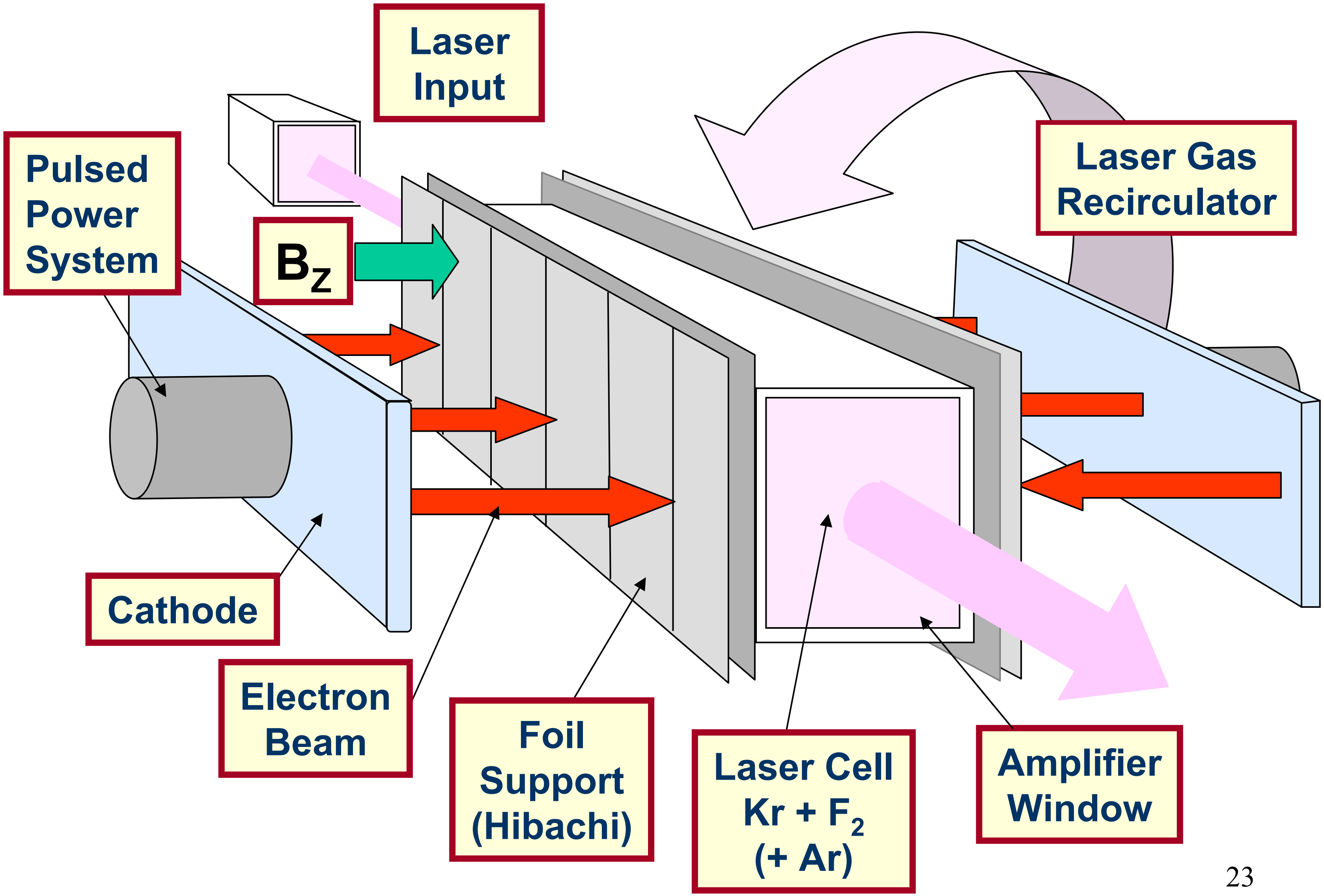
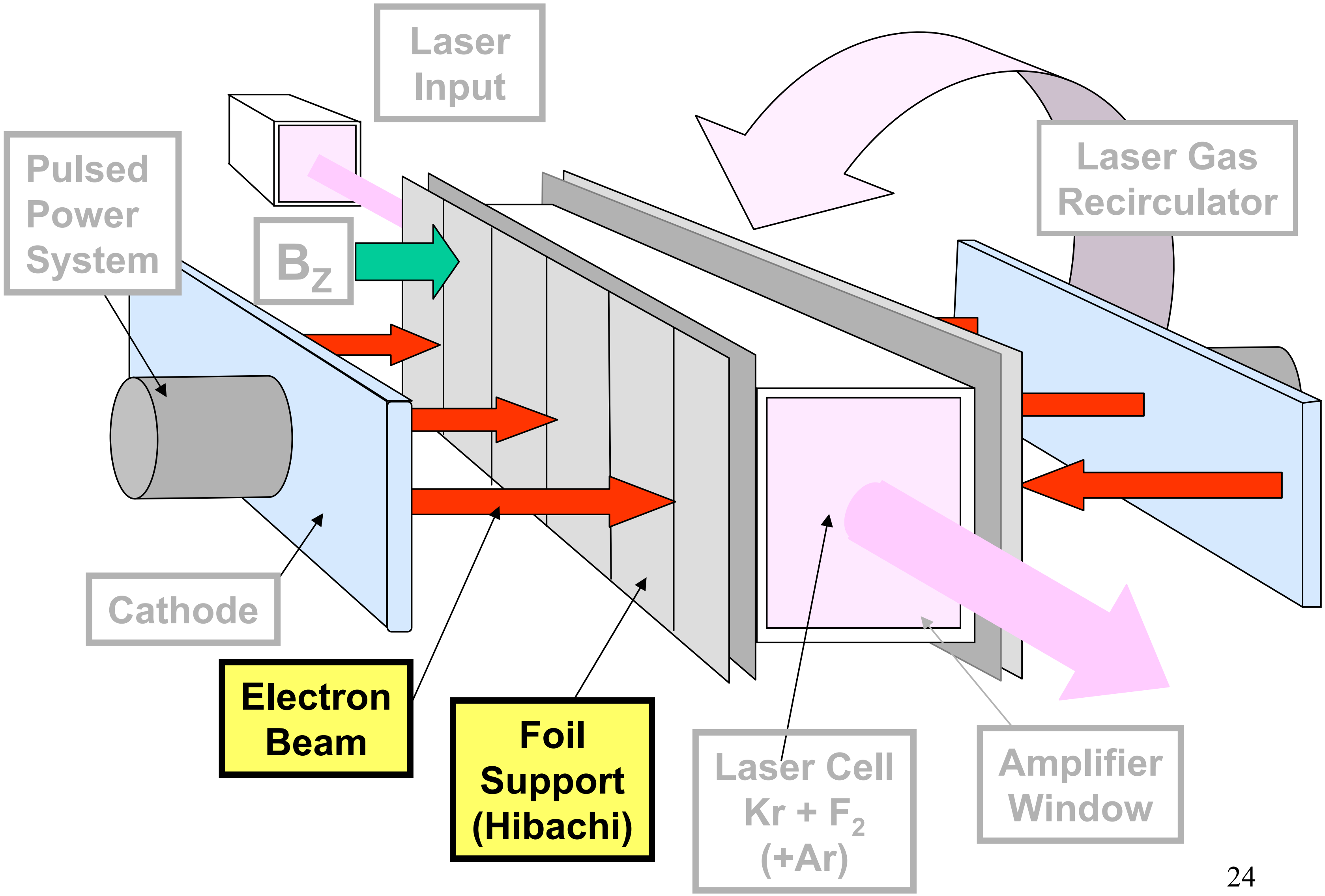
The key components of a Krypton Fluoride (KrF) Laser

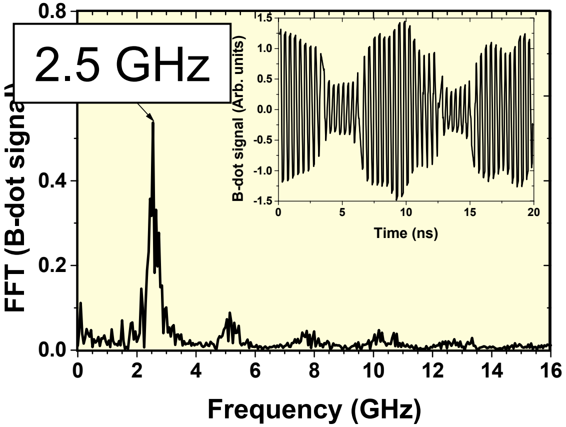


Electron beam propagation, transport, and deposition

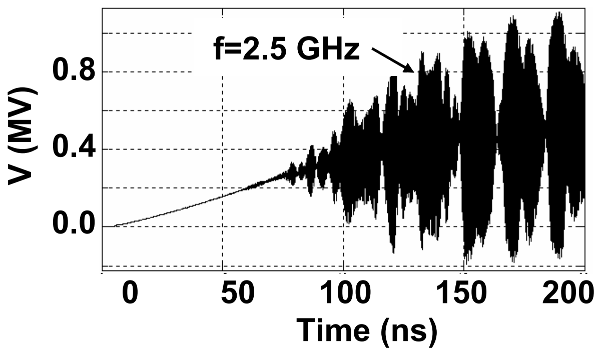


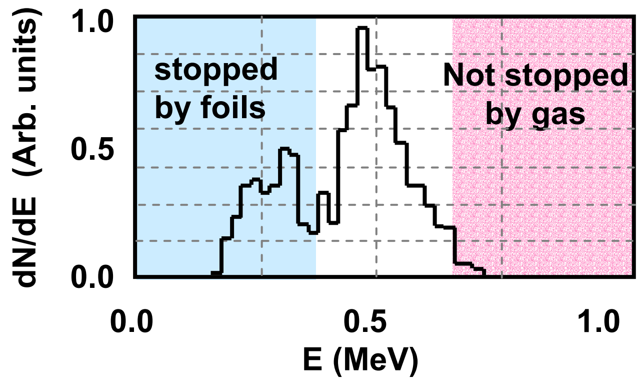
Experiments and 2-D models show "Transit Time" Instability in large area, low impedance diodes

Experiment (Nike)

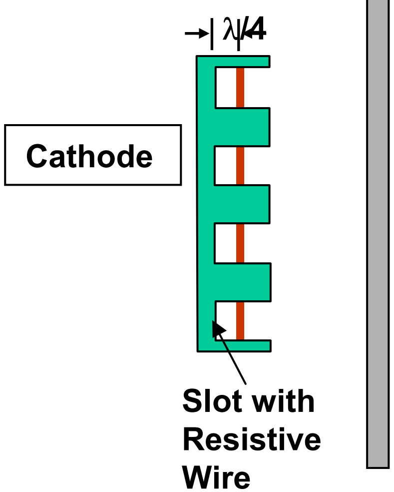


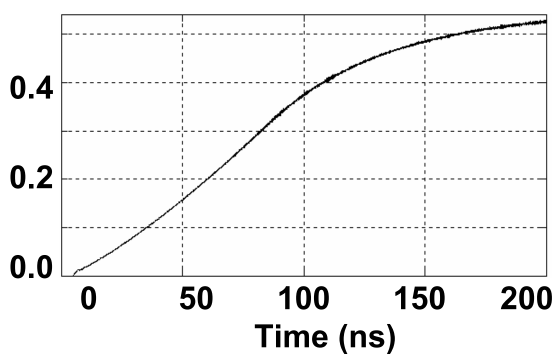
Theory

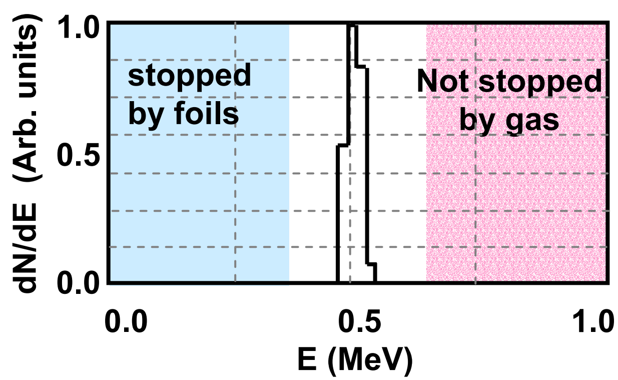




Theory: mitigate instability by adding resistively tuned slots in cathode

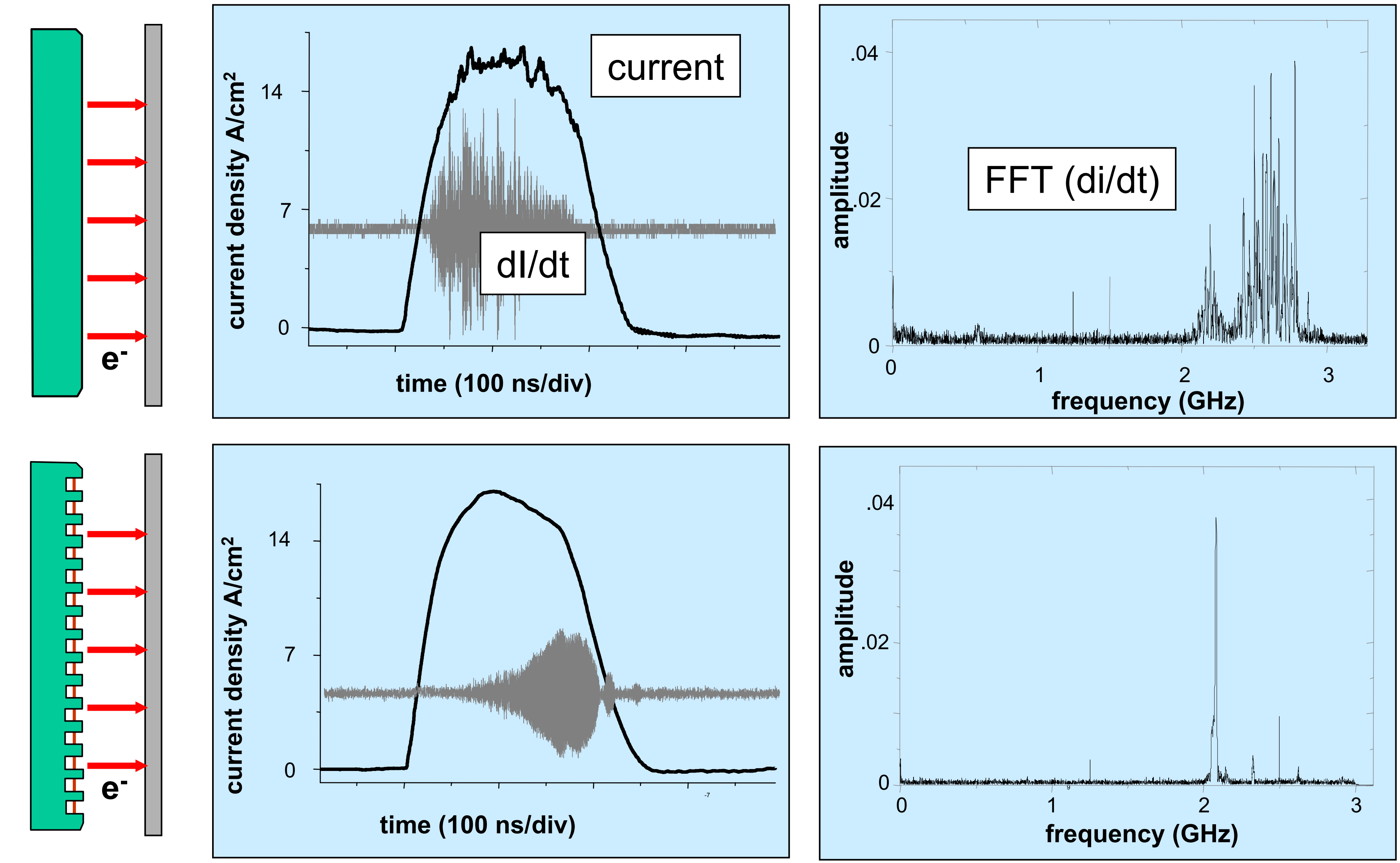






M. Friedman, et al et al Appl. Phys. Lett. **77,** 1053 (2000)

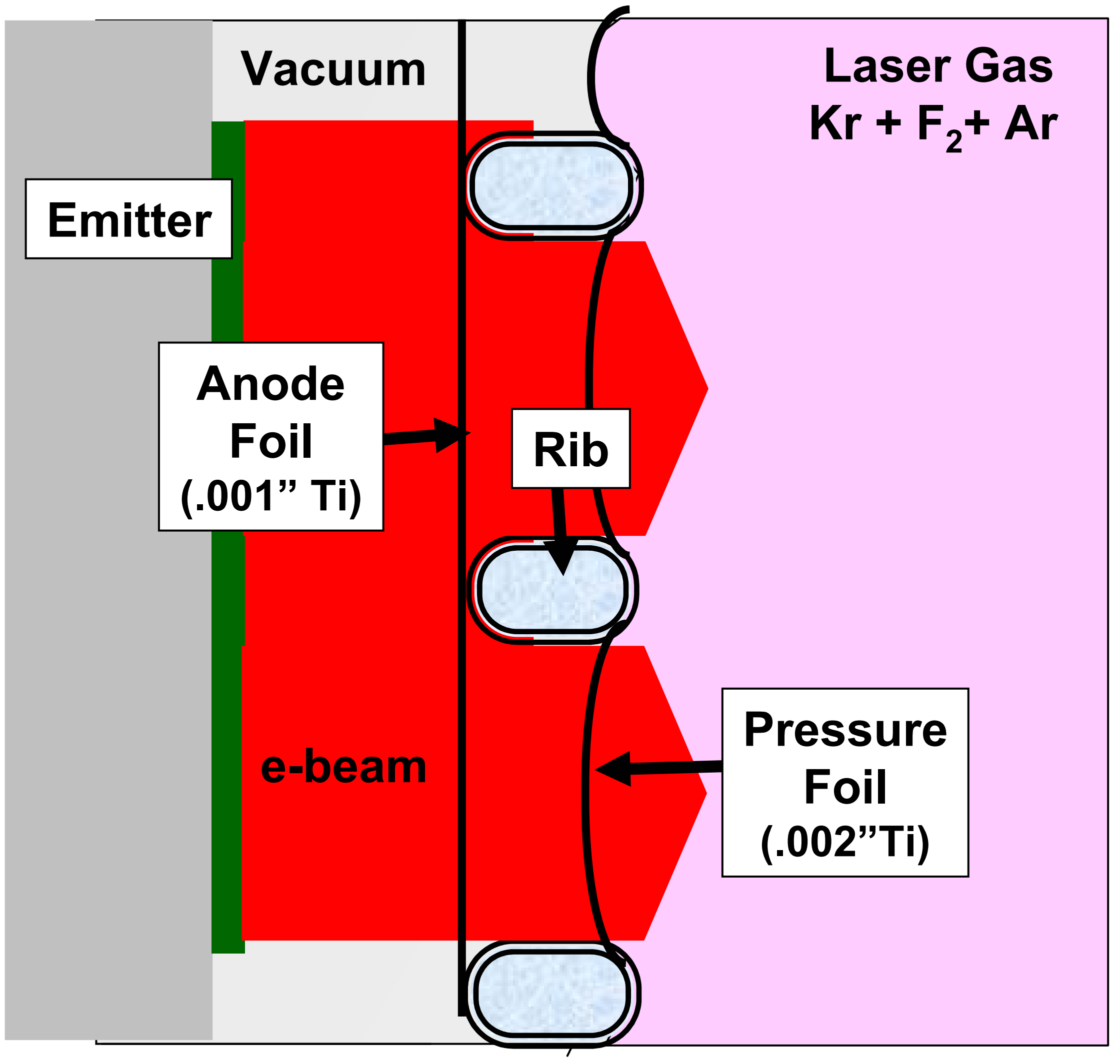
Slotting cathode reduces transit-time instability on Nike 60 cm Amplifier



Adding Resistors or slotting cathode in other direction is expected to eliminate instability

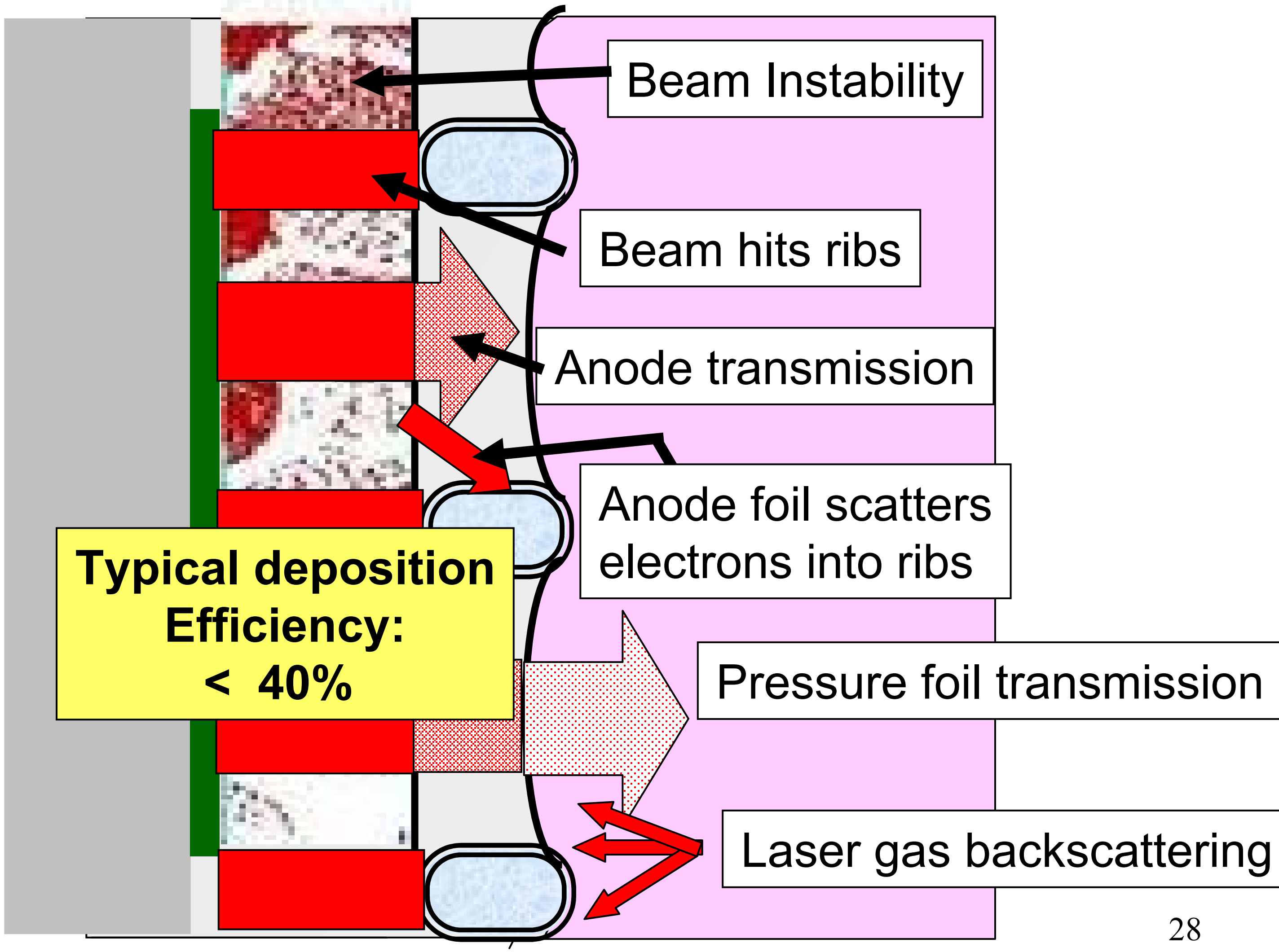
M. Friedman, S.B. Swanekamp, et al Appl. Phys. Lett. **81,** 1597 (2002)

"Conventional" Cathode/Hibachi: monolithic cathode, anode foil, ribs, + pressure foil…



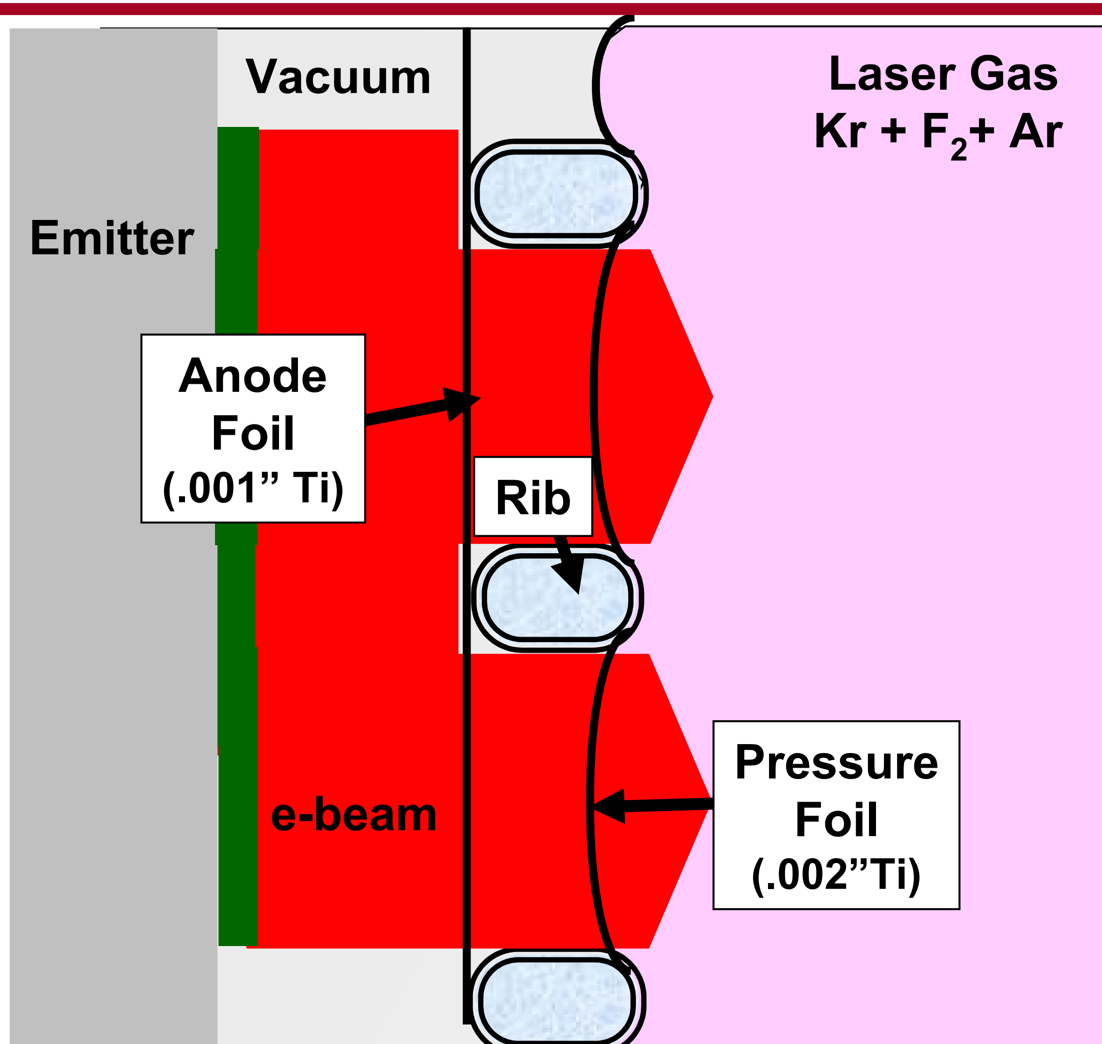
"Conventional" Cathode/Hibachi: monolithic cathode, a smooth anode, ribs, + pressure foil…

…..and lots of losses



Two innovations allowed high hibachi transmission:

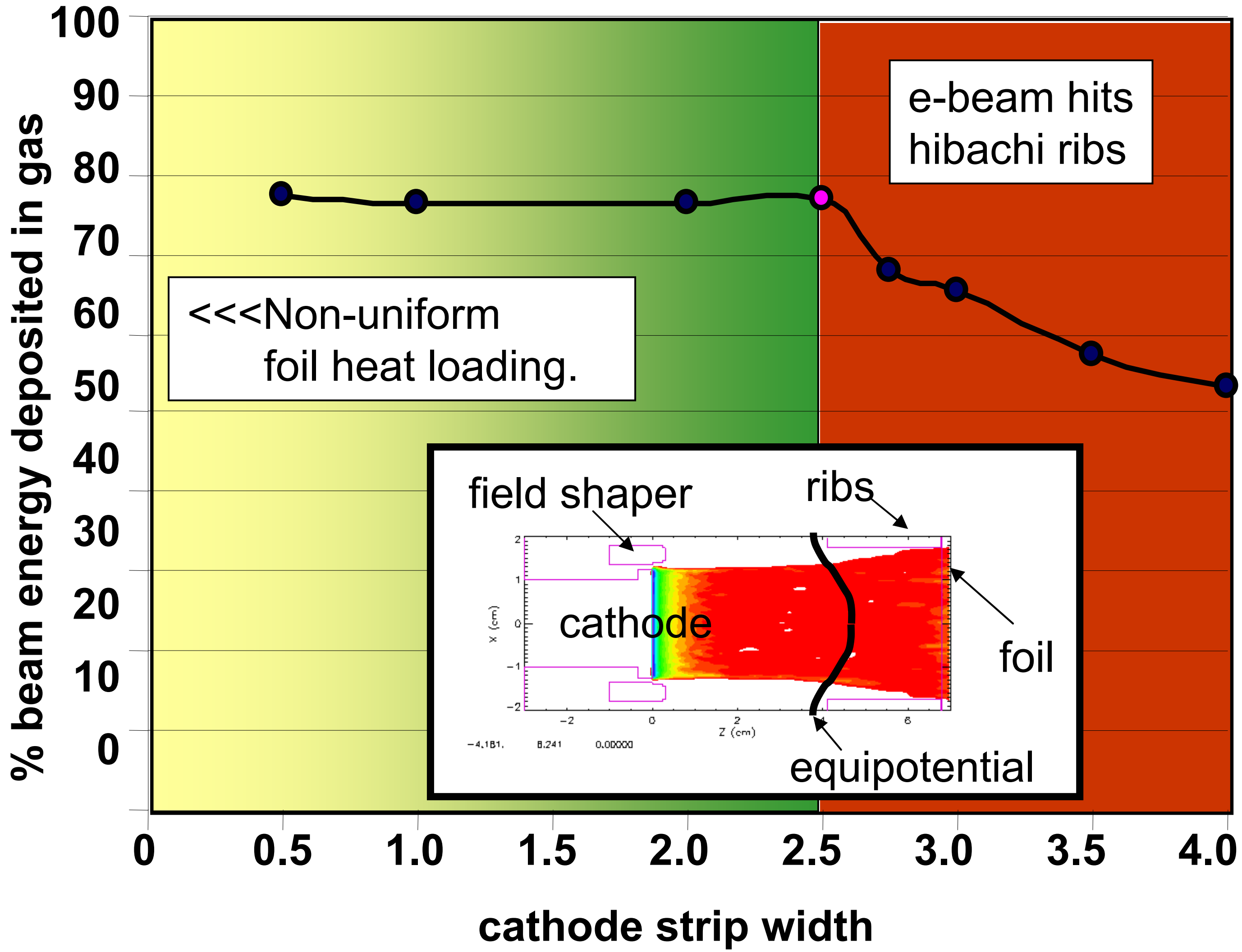
1. Eliminate anode foil
2. Pattern the beam to “miss” the ribs



ISSUES

1. **Non-uniform electric field at anode causes beam spreading**
2. **Beam rotates and skews between cathode and anode due to B_z**

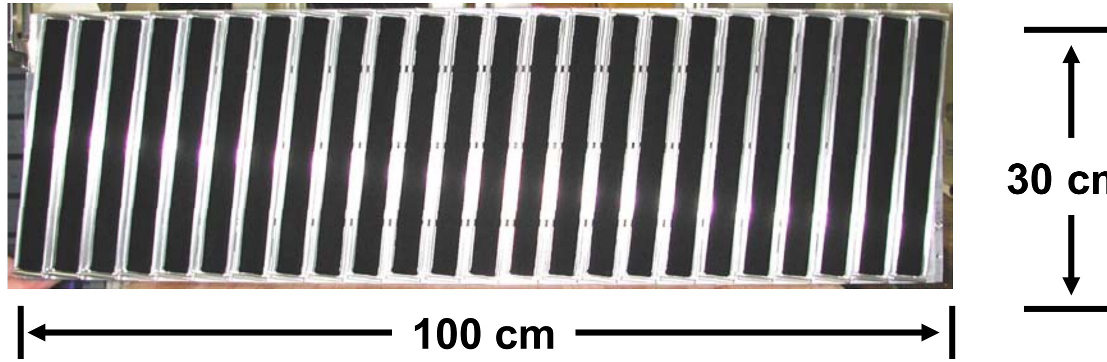
LSP modeling prescribes cathode width needed to accommodate beam spreading



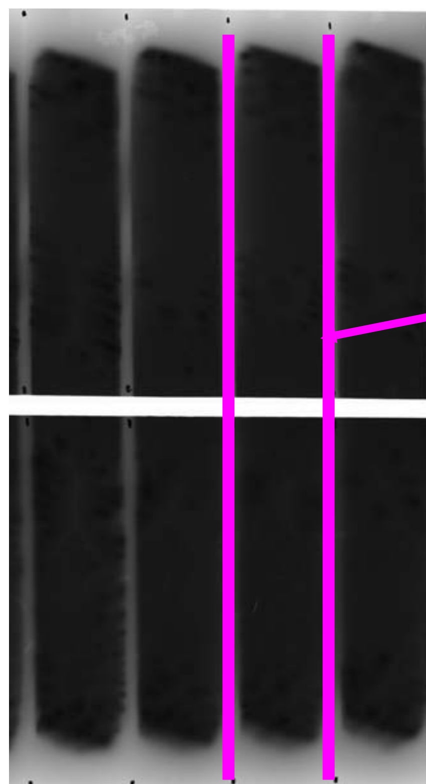
Simulations by D. Rose & D. Welch, MRC Albuquerque

We can counter-rotate the emitter strips so beam goes straight through the hibachi ribs

Cathode strips rotated 6 degrees



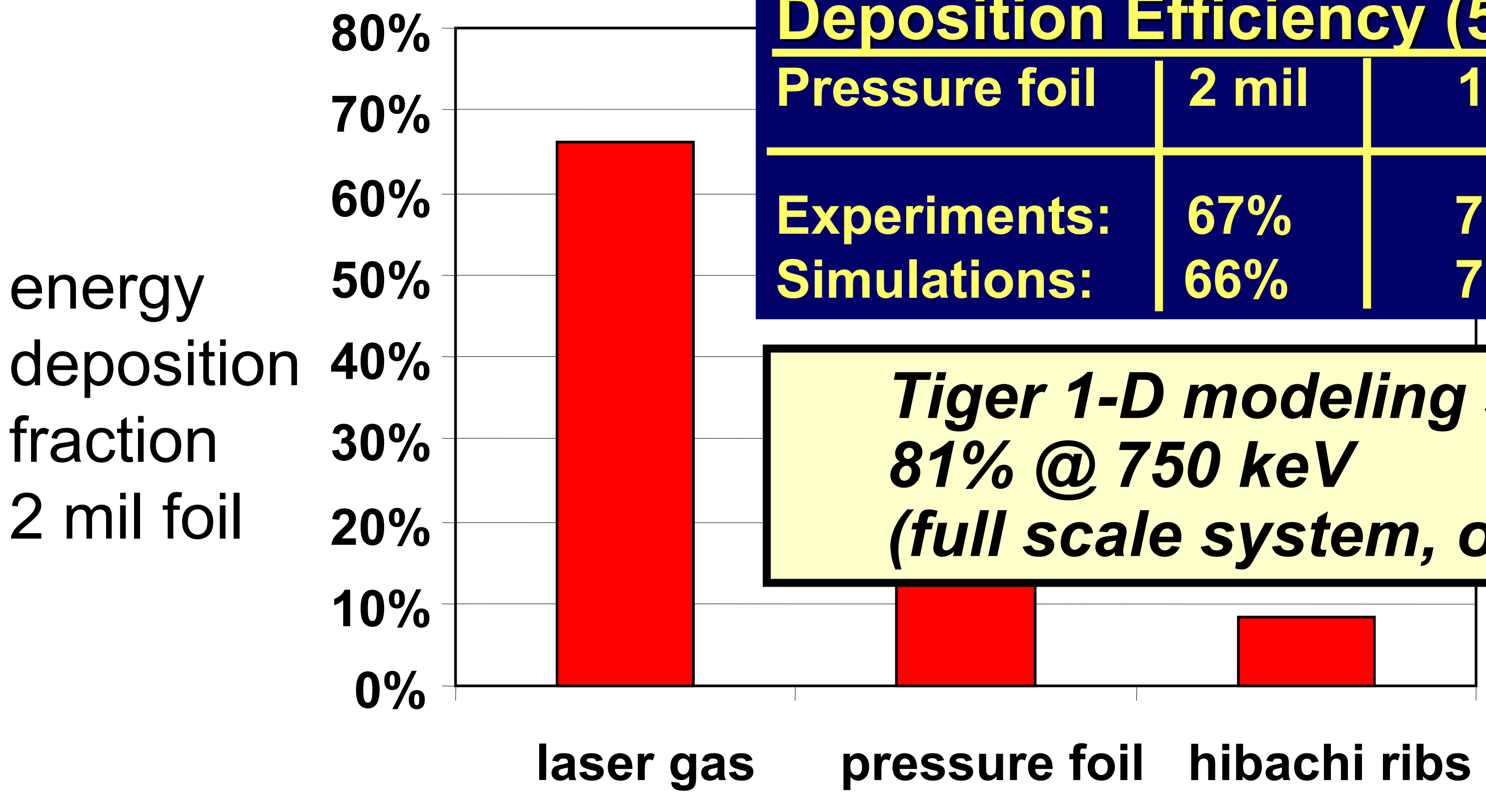
Radiachromic Film:
Time integrated current profile at the pressure foil



Position of the hibachi ribs

3-D LSP Simulations (MRC/Albuquerque)

- Prescribe the cathode rotation
- Predict observed electron beam deposition into the gas



Deposition Efficiency (500 keV):

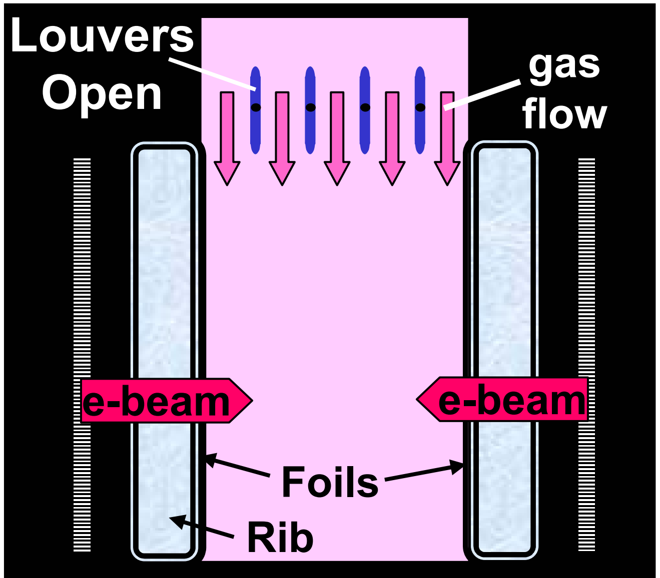
Pressure foil	2 mil	1 mil
Experiments:	67%	75%
Simulations:	66%	76%

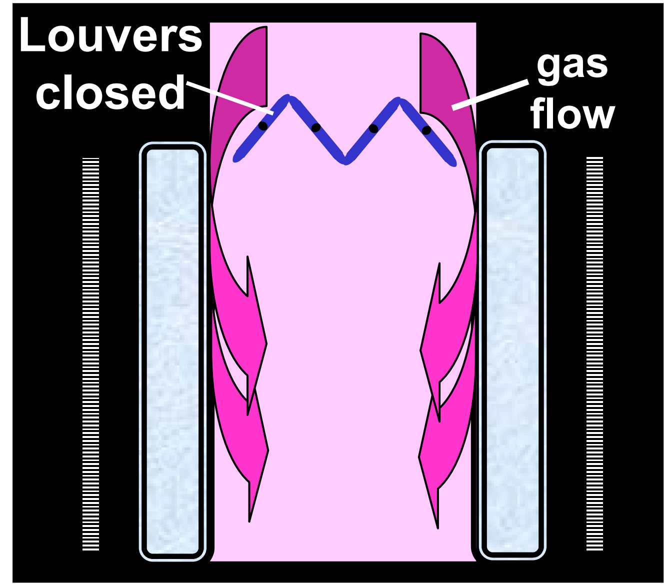
Tiger 1-D modeling shows 81% @ 750 keV (full scale system, or Nike)

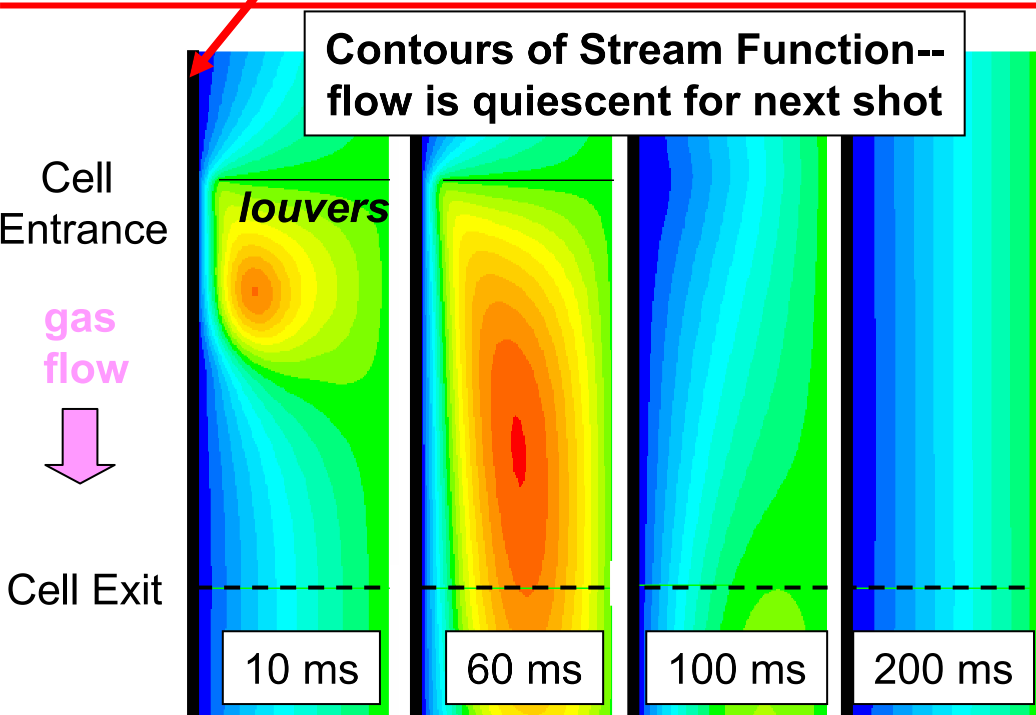
Efficiency ≡ Energy deposited in laser gas/energy in diode (for flat top portion of beam)

Simulations by D. Rose & D. Welch, MRC Albuquerque

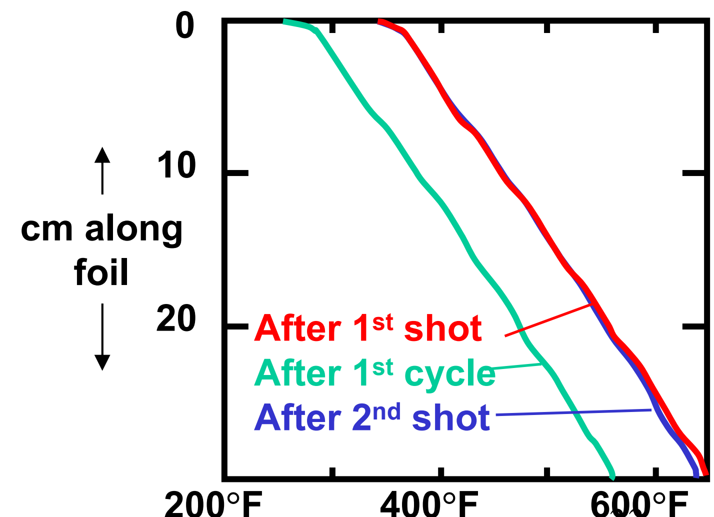
The recirculating laser gas can be used to cool the Hibachi





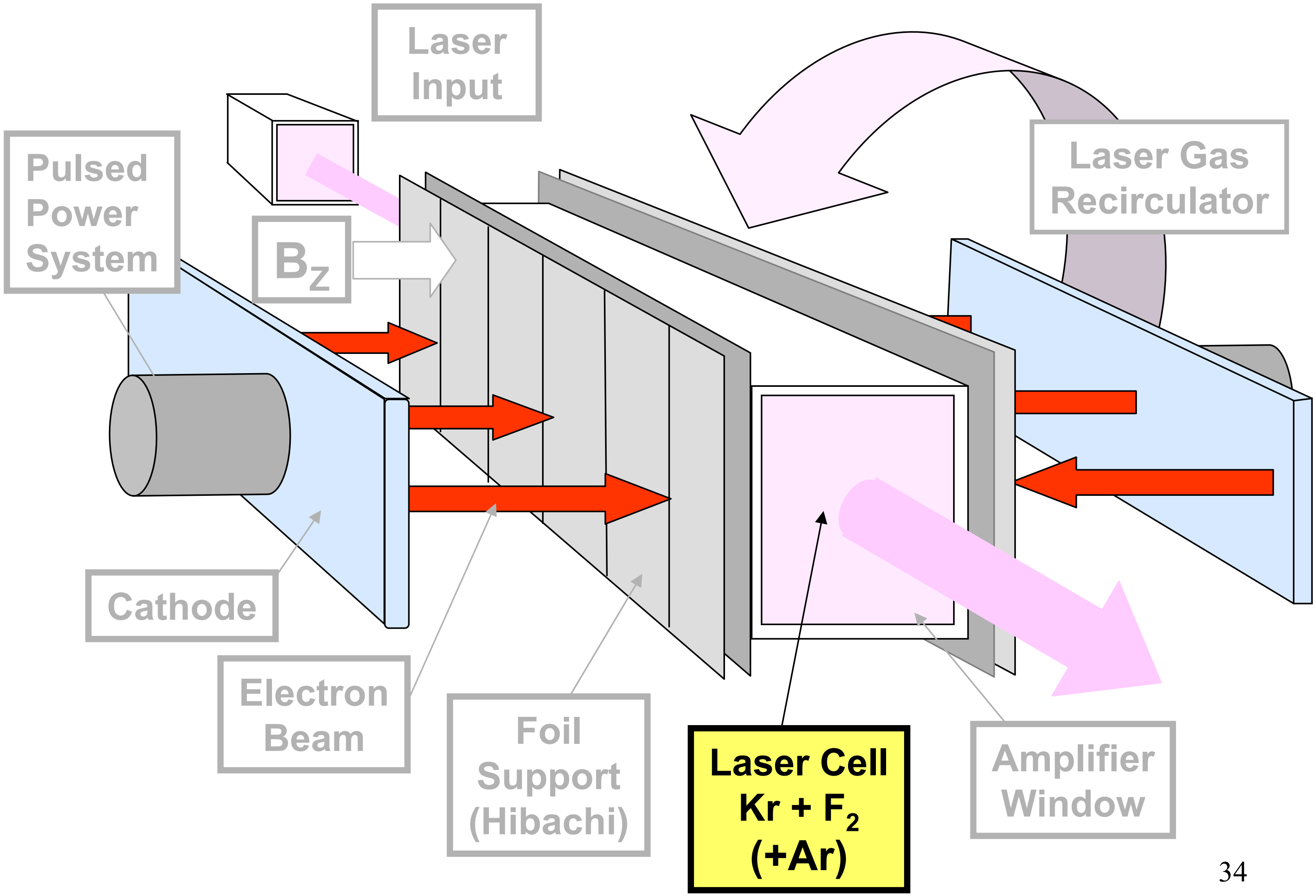


Foil Temperature below required 650°F



Concept & Modeling:
A.Banka & J.Mansfield, Airflow Sciences, Inc

KrF physics



Laser Input
Pulsed Power System
B_z
Laser Gas Recirculator
Cathode
Electron Beam
Foil Support (Hibachi)
Laser Cell
$Kr + F_2$
(+Ar)
Amplifier Window

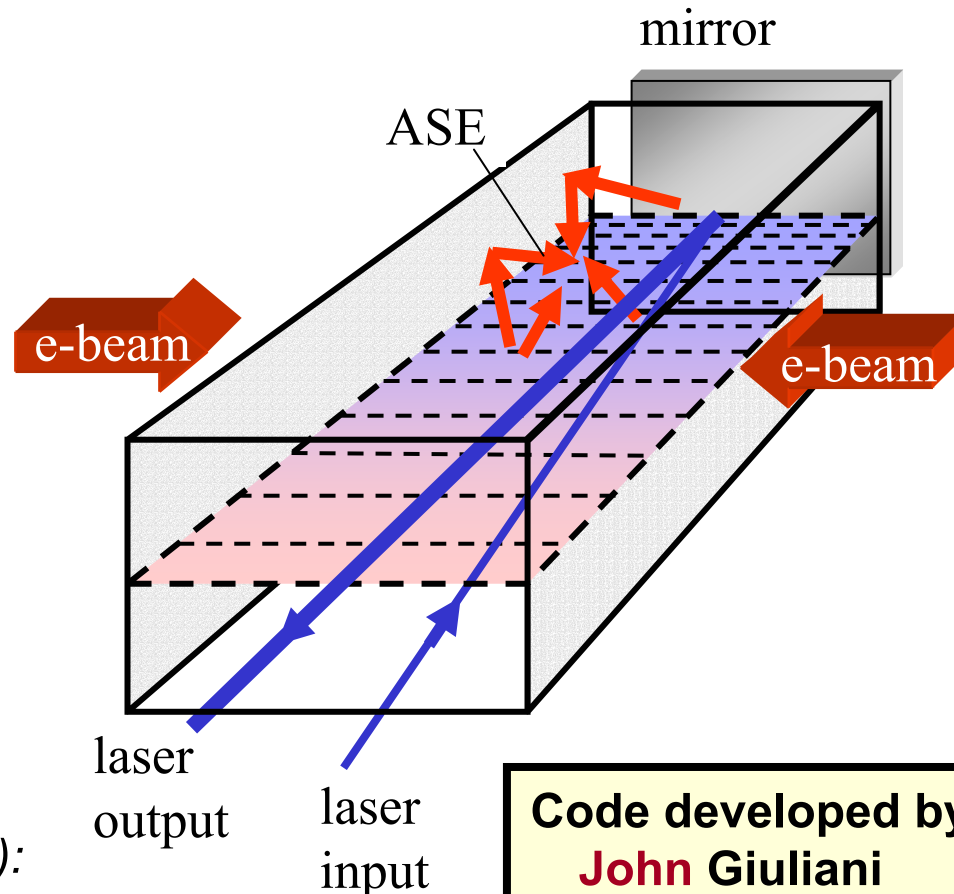
"Orestes":
Combines relevant physics into a single KrF Physics code

electron beam:
ionization and excitation from
Boltzman analysis

plasma:
1D axially resolved, separate
electron and gas temperatures

kinetics:
24 species, 122 reactions
includes KrF vibrational structure

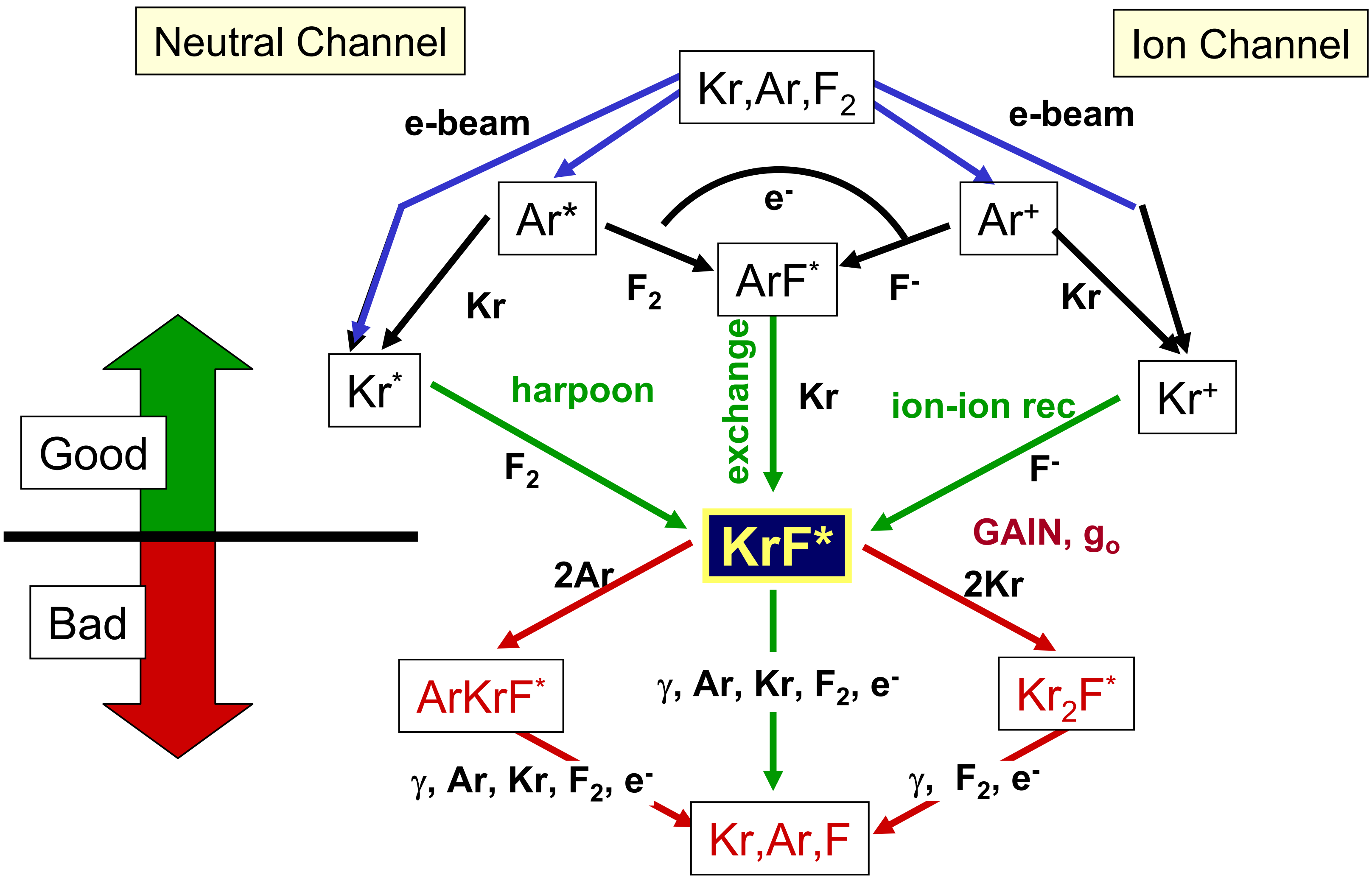
lasing and ASE:
(Amplified Spontaneous Emission):
3D, time dependent,
ASE gain narrowing



Code developed by:
John Giuliani
Paul Kepple
George Petrov
Bob Lehmberg

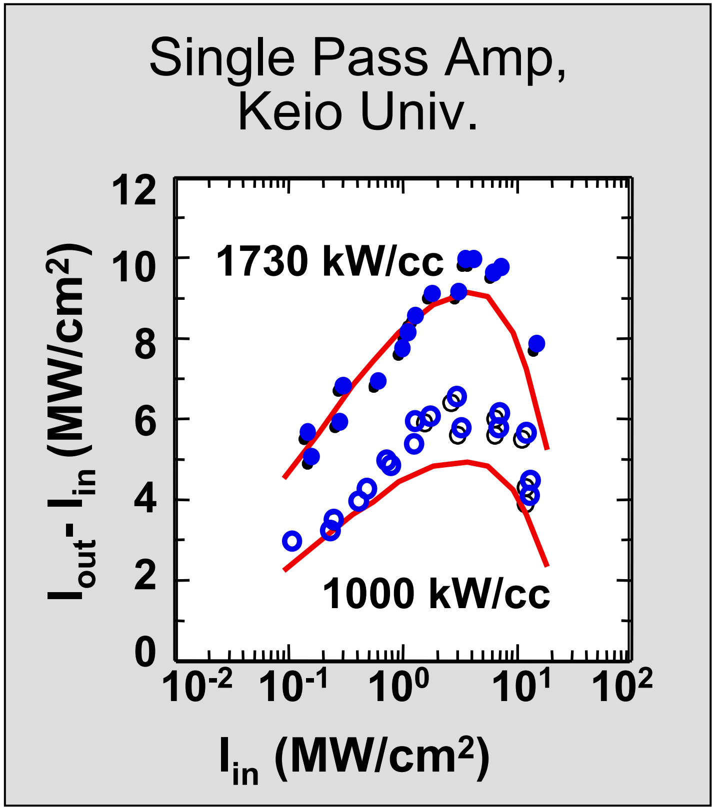
KrF Kinetics is a complex process

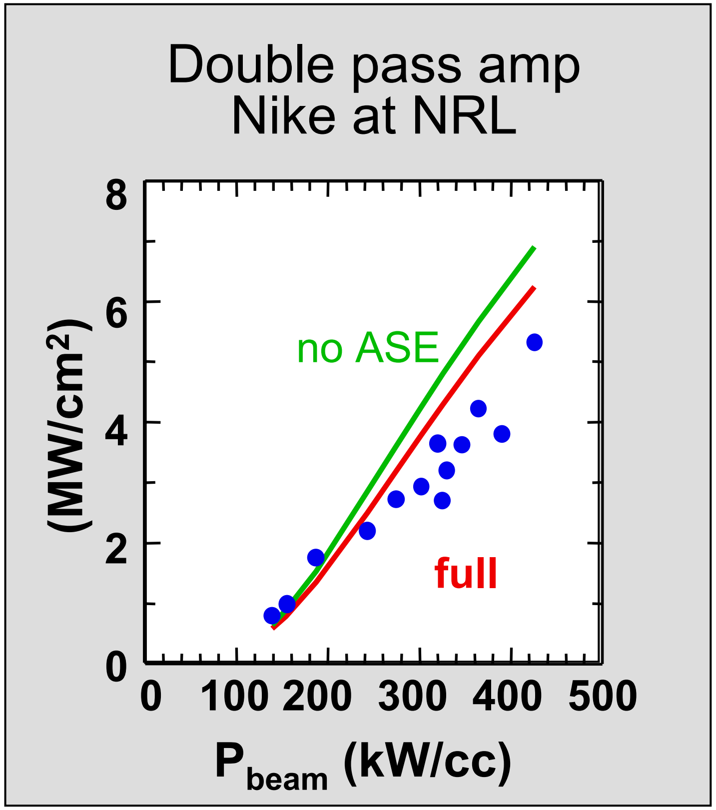
24 species, 122 reactions



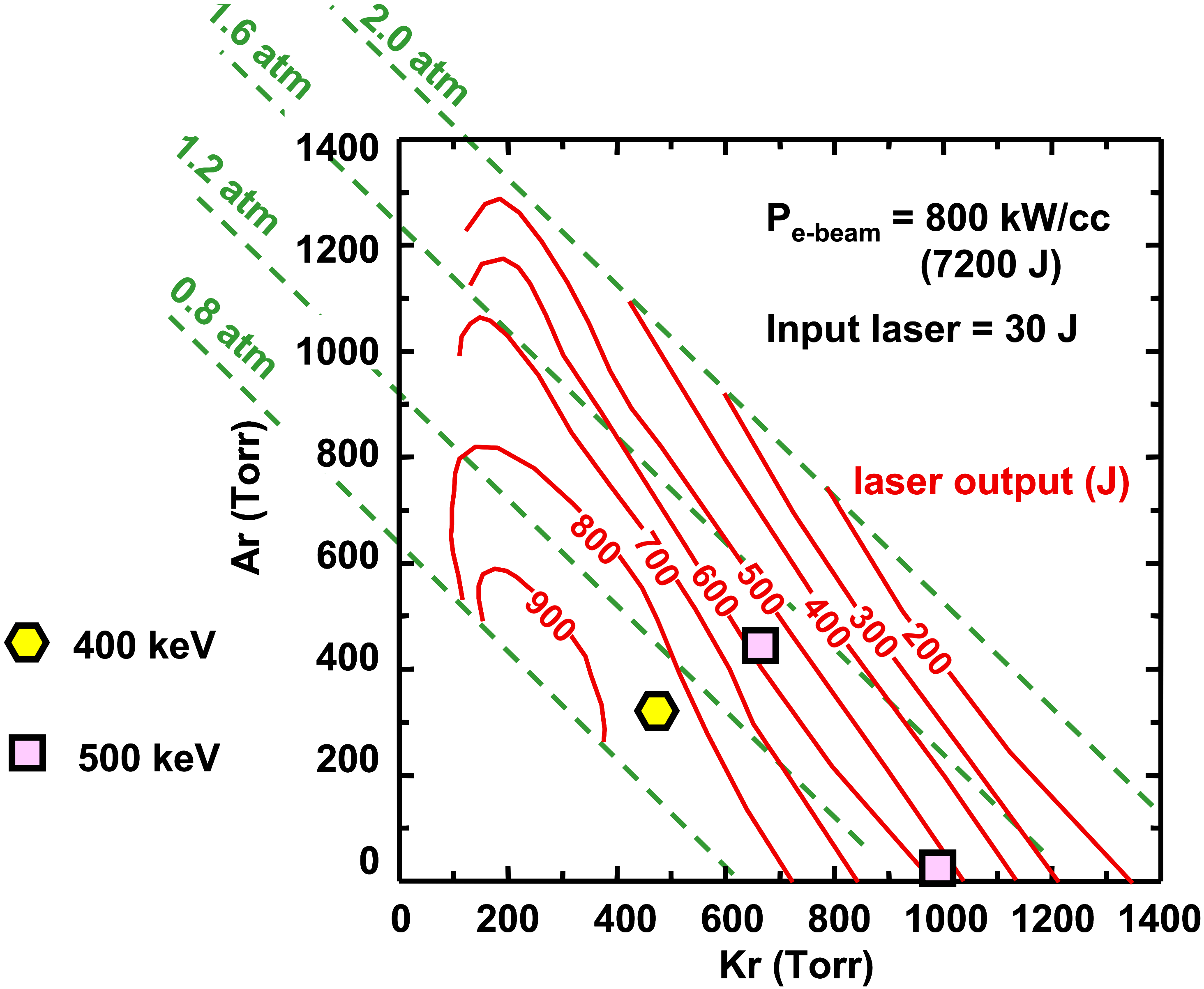
absorption, $\sigma = \sigma_{F2}\eta_{F2} + \sigma_{F-}\eta_{F-} + \sigma_{KrF2}\,\eta_{KrF2} + \sigma_{ArF2}\,\eta_{ArF2}$

Orestes predicts KrF Laser yields under a wide range of operating conditions

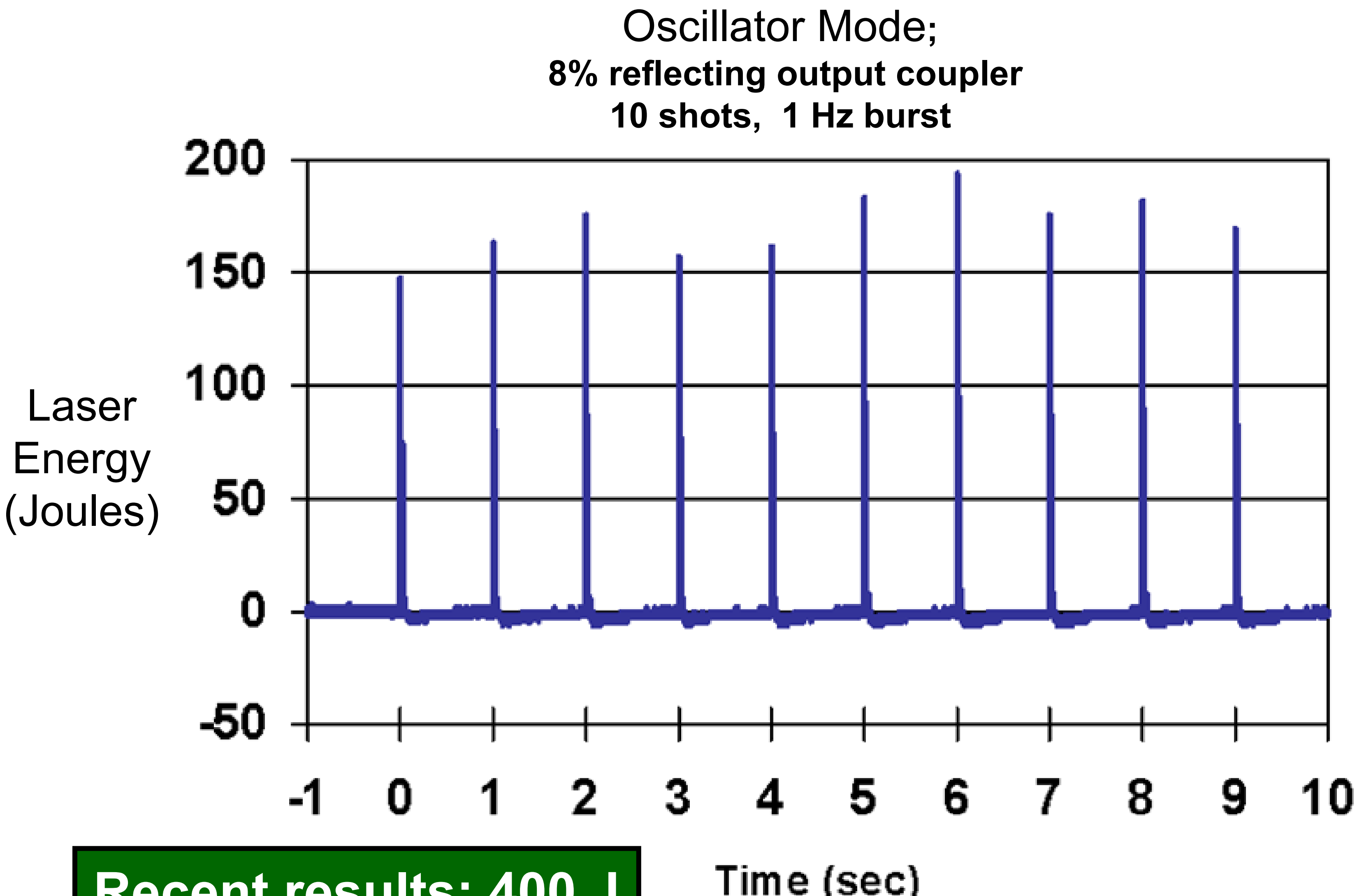




ORESTES prediction of Electra performance

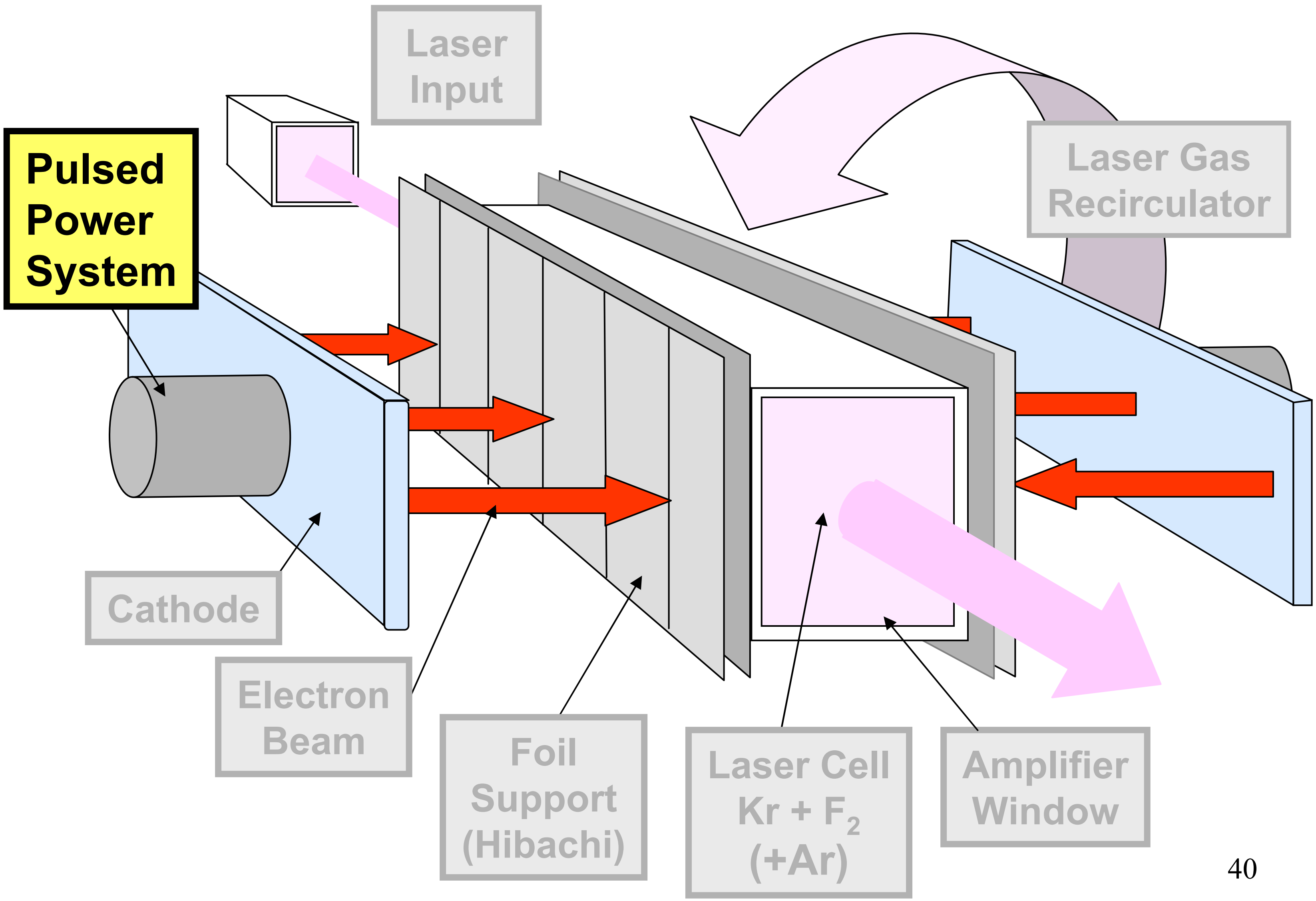


The Electra KrF Laser has achieved first light

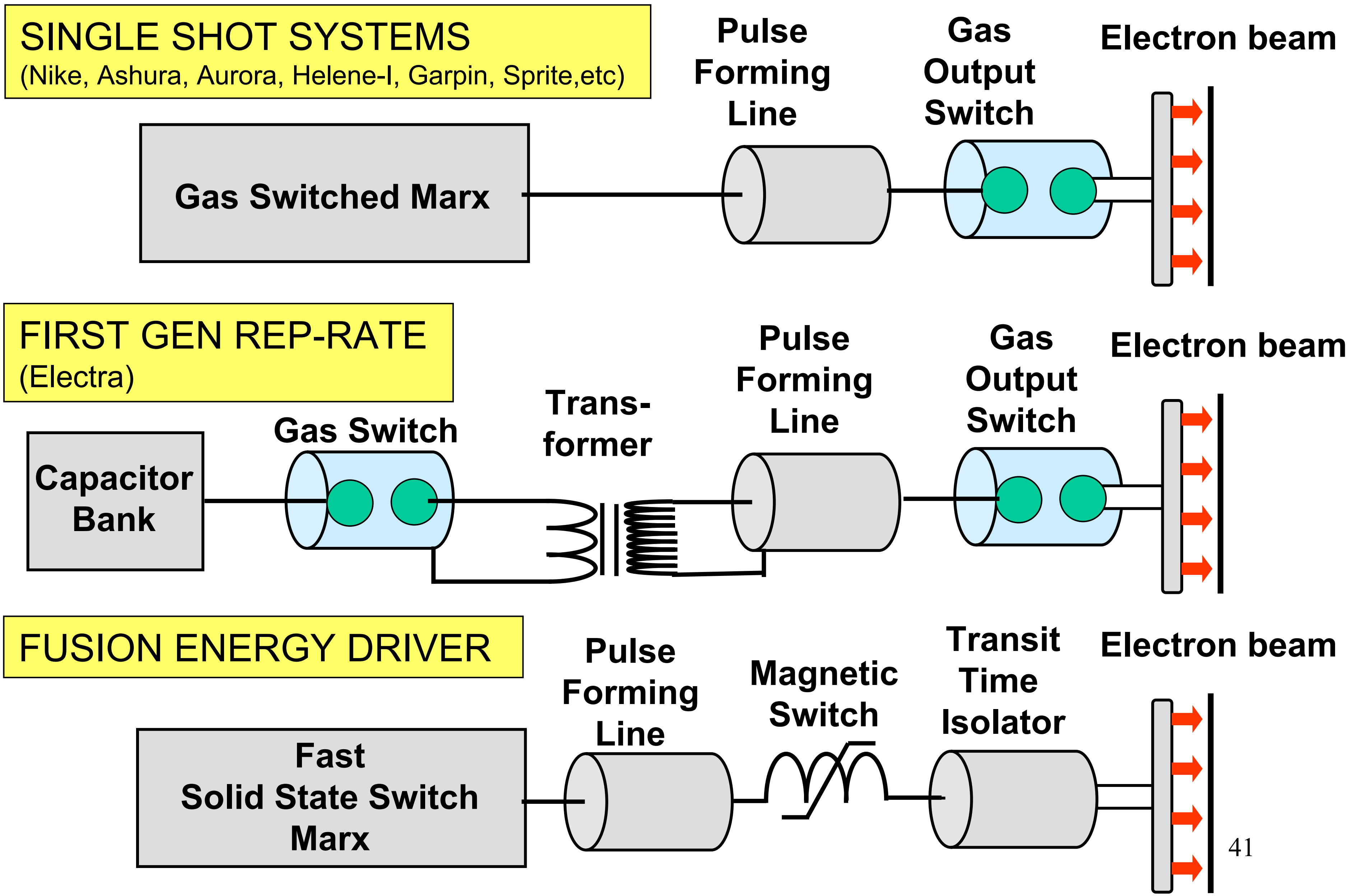


Recent results: 400 J

Pulsed Power



Evolution of pulsed power for KrF lasers



Advanced Laser Gated and Pumped Thyristor

Flood entire switch volume with photons….

> *fast switching times: ~ 100 nsec*

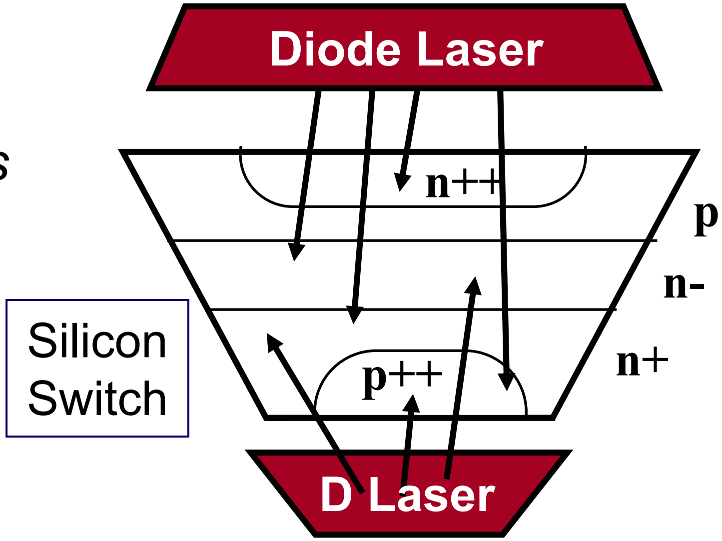
> *Reduces number of compression stages*

Continuous laser pumping reduces losses

> *efficient*

Four junction device

> *enables ~20 kV working devices*



Demonstrated 1st generation
3.2 kV, 2.7 kA/cm², 5 Hz
based on standard switch

Tested 2nd generation
15.2 kV
advanced construction

Main points of the talk

What is a KrF Laser?

Electron beam pumped gas laser

KrF Lasers and Inertial Fusion Energy

Strengths: Beam uniformity, zooming, cost, scale to large systems
R&D required: efficiency and durability

The Physics and Technologies of KrF Lasers

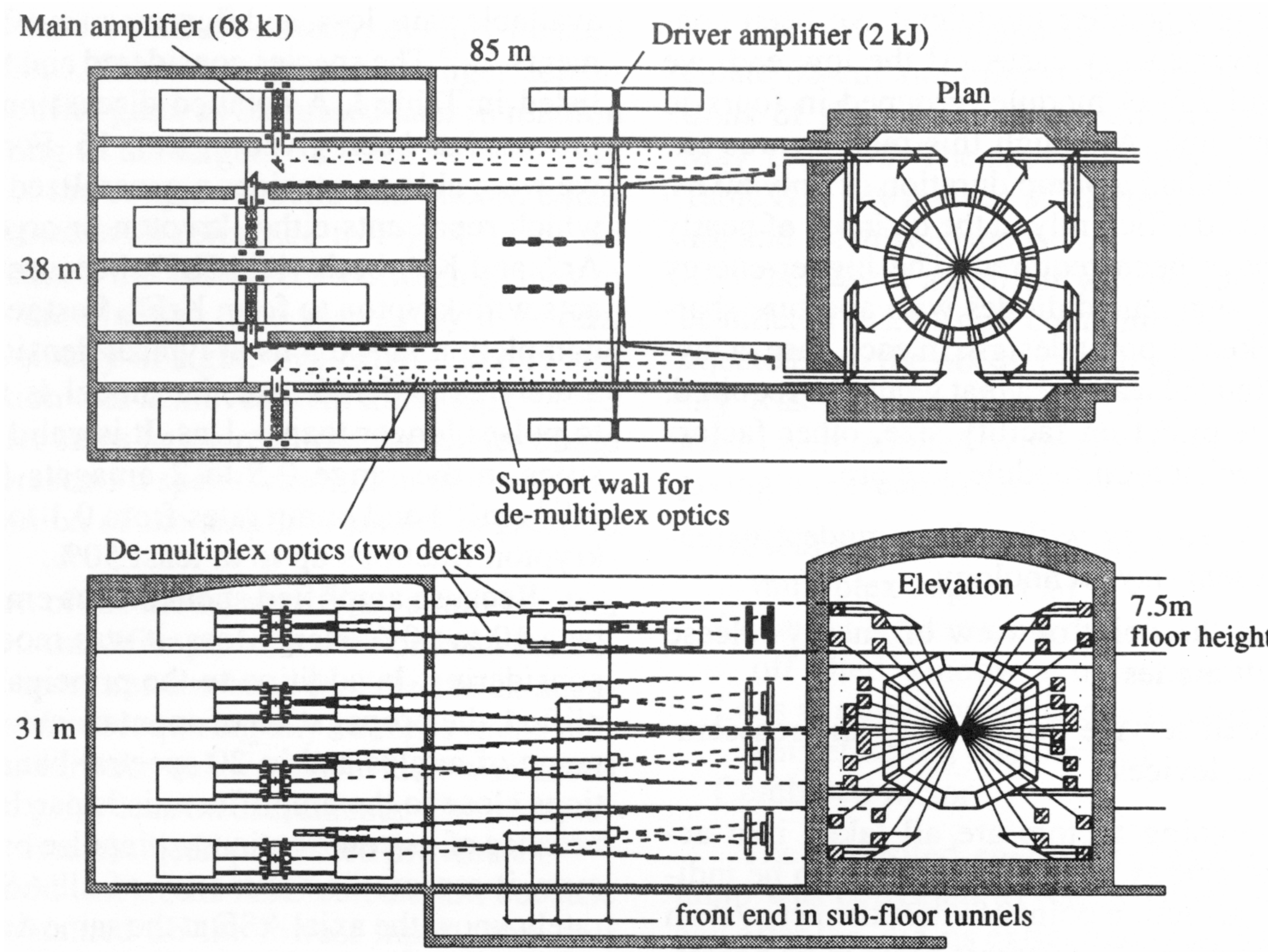
Electron beam propagation, transport, and deposition
KrF Kinetics
Pulsed Power

Phased program to develop a KrF Fusion Driver

Part of an integrated program to develop laser fusion energy

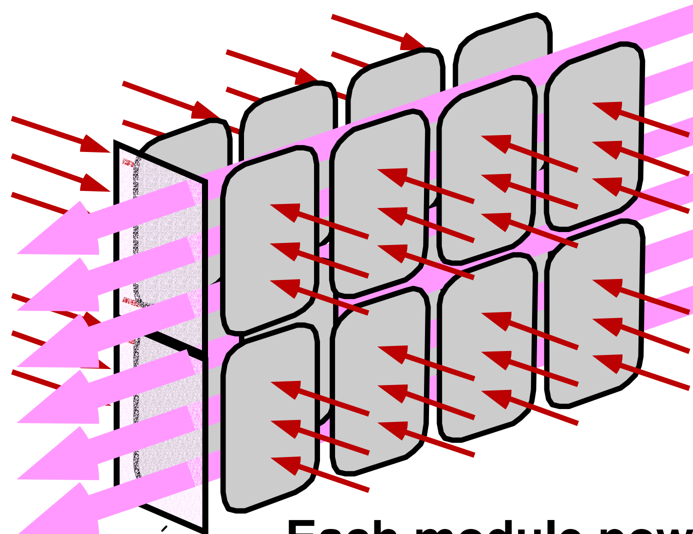
A generalized picture of a KrF Laser fusion power plant

M.W. McGeoch et al Fusion Technology, **32,** 610 (1997)



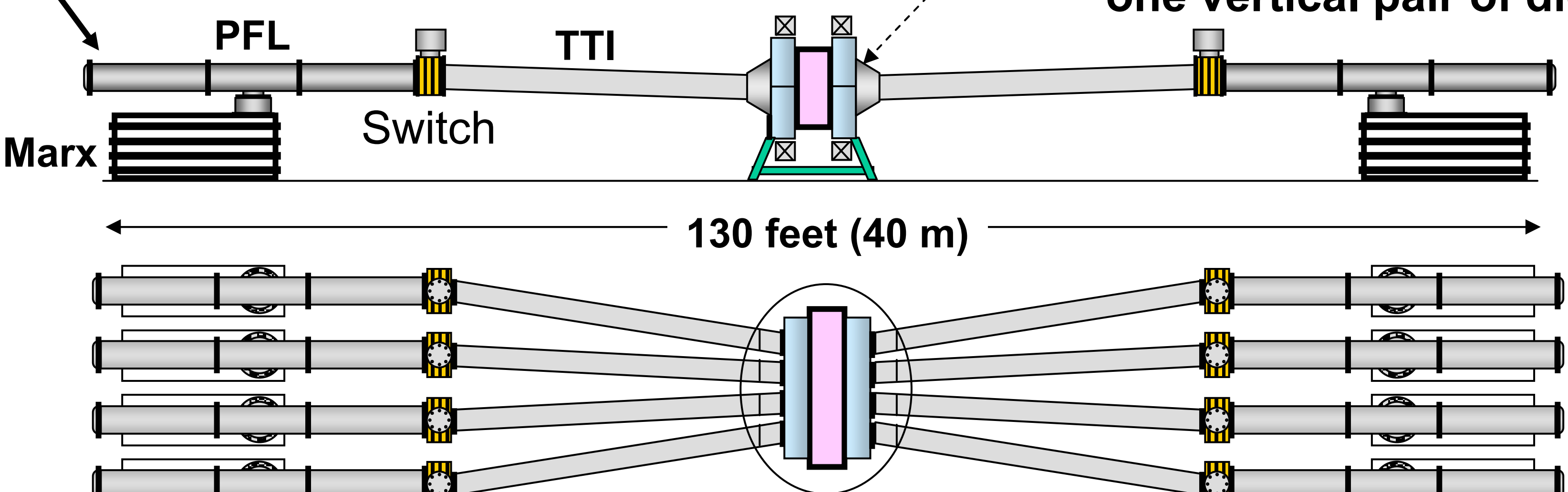
A 60 kJ Amplifier

E_{stored}	100 kJ x 8 = 800 kJ
V, I, τ:	800 keV, 84 kA x 16, 600 ns
Energy in gas:	**544 kJ**
Laser Input:	**4 kJ**
Laser Output:	**57.8 kJ (η = 10.8%)**



Each module powers one vertical pair of diodes

100 kJ Pulsed Power Module

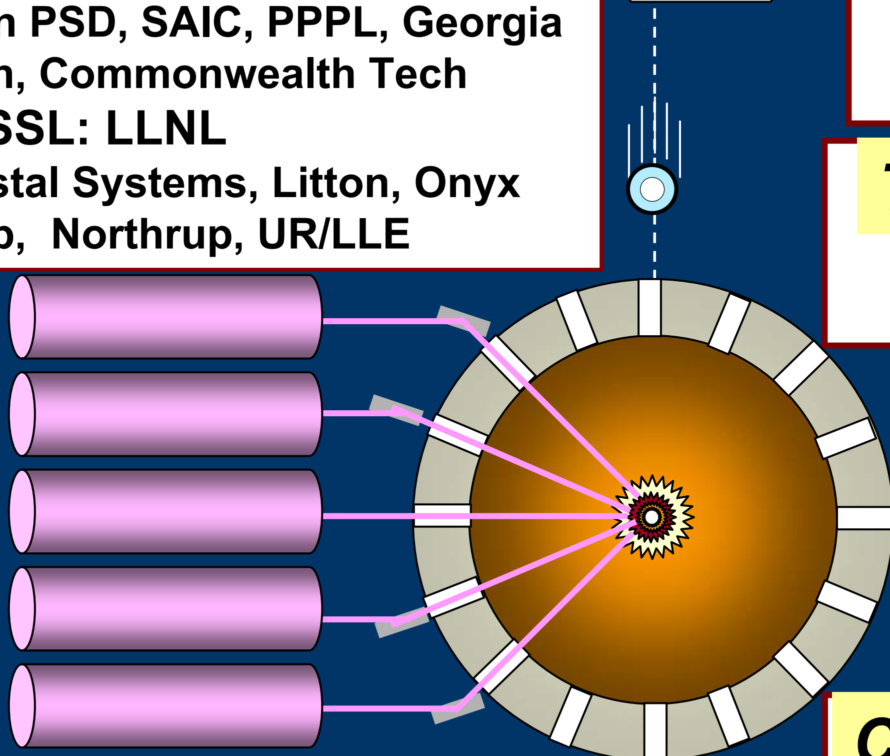


KrF Laser Development is part of a coordinated National Program to develop Laser IFE as an integrated system.
(8 Government labs, 7 Universities, 8 Private Industries)

Lasers

KrF: NRL
Titan PSD, SAIC, PPPL, Georgia Tech, Commonwealth Tech
DPSSL: LLNL
Crystal Systems, Litton, Onyx Corp, Northrup, UR/LLE

Target factory



Target Fabrication

GA: Fab, charac, mass production
LANL: Adv foams
SCHAFER: DvB foams

Target Injection

GA: Injector, Injection & Tracking
LANL: DT mech prop, thermal resp.

Direct Drive Target Design

NRL- Target design
LLNL: Yield spectrum, design

Chambers and Materials

WISCONSIN: Yield spectrum / Chambers
LLNL: Alt chamber concepts, materials
UCSD/ANL/INEEL: Chamber dynamics
SNL: Materials response x-rays/ions
ORNL/UCLA/UCSB/Wisconsin: Materials

Final Optics

LLNL: X-rays, ions, neutrons
UCSD: Laser, debris mitigation

A phased program to develop Laser Fusion Energy

IFE DEMO

- *Demonstrate useable electrical power from Fusion*

Phase III
Engineering Test Facility
start ~2014-16, operating ~ 2022

- *2-3 MJ, 60 laser beam lines*
- *High gain target implosions*
- *Optimize materials & components.*
- *~ 300 MW electricity (burst mode)*

Phase II
Integrated Research Experiments and more
start ~2006

Establish:
Target physics
Full scale Laser technology
Target Mass Production
Injection/tracking in Chamber
Final Optics
Power Plant design

Phase I:
Science and technology
Start 1999

Develop Viable:
Scalable Laser Technologies
Target designs
Target fab/ injection
Final optics
Chamber Concept

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